11-4403-cv

United States Court of Appeals

for the

Second Circuit

AEGIS INSURANCE SERVICES, INC., LIBERTY INSURANCE UNDERWRITERS, INC., NATIONAL UNION INSURANCE COMPANY OF PITTSBURGH, NUCLEAR ELECTRIC INSURANCE LIMITED, CERTAIN UNDERWRITERS AT LLOYDS, (Syndicates 1225 and 1511), as subrogor of Consolidated Edison Company of New York, Inc., and CONSOLIDATED EDISON COMPANY OF NEW YORK, INC.

Plaintiffs-Appellants,

(For Continuation of Caption See Inside Cover)

ON APPEAL FROM THE UNITED STATES DISTRICT COURT
FOR THE SOUTHERN DISTRICT OF NEW YORK

JOINT APPENDIX
Volume 11 of 16 (Pages JA-2866 to JA-3066)

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(For Continuation of Appearances See Inside Cover)

v.

7 WORLD TRADE COMPANY, L.P.,

Defendant-Cross-Defendant-Cross-Claimant-Third-Party Plaintiff-Appellee,

CITIGROUP INC., CITIGROUP GLOBAL MARKETS HOLDINGS INC., SALOMON SMITH BARNEY HOLDINGS, INC., SALOMON INC., SILVERSTEIN DEVELOPMENT CORP., SILVERSTEIN PROPERTIES, INC.,

Defendants-Cross-Defendants-Cross-Claimants-Appellees,

TISHMAN CONSTRUCTION CORPORATION,

Defendant-Cross-Defendant-Appellee,

OFFICE OF IRWIN G. CANTOR, P.C., FLACK & KURTZ, INC.,

Defendants-Cross-Defendants-Third-Party Defendants-Appellees,

SWANKE HAYDEN CONNELL ARCHITECTS, SYSKA & HENNESSY GROUP, INC., AKA SYSKA & HENNESSY ENGINEERS,

Defendants-Cross-Defendants-Cross-Claimants-Third-Party Plaintiffs,

H.O. PENN MACHINERY CO., INC., ALL FIRE SYSTEMS, INC.,

Defendants-Cross-Defendants-Cross-Claimants,

GRACE CONSTRUCTION PRODUCTS, EMERY ROTH & SON, P.C., SECURITAS AB, SECURITY SERVICES, INC., CENTIFUGAL ASSOCIATES, INC., SYSKA & HENNESSY, INC.,

Defendants-Cross-Defendants,

AMBASSADOR CONSTRUCTION CO., INC., COSENTINI ASSOCIATES INC., CANTOR SEINUK GROUP, P.C., SKIDMORE OWINGS AND MERRILL, L.L.P., AMBASSADOR CONSTRUCTION CO., INC., AMEC CONSTRUCTION MANAGEMENT, INC., FKA MORSE DIESEL INTERNATIONAL, INC.,

Defendants-Cross-Defendants-Third-Party Defendants,

DIC/UNDERHILL, a joint venture, KABACK ENTERPRISES, PREFERRED UTILITIES MANUFACTURING CORP., ELECTRIC POWER SYSTEMS, INC., G.C. ENGINEERING & ASSOCIATES, P.C., FIRECOM INC., FIBERLOCK TECHNOLOGIES, INC., ROSEBWACH TANK CO., INC., ABCO PEERLESS SPRINKLER CORPORATION, AMR CORPORATION, AMERICAN AIRLINES, INCORPORATED, UAL CORPORATION, UNITED AIRLINES INCORPORATED, COLGAN AIR, INCORPORATED, US AIRWAYS GROUP, INCORPORATED, US AIRWAYS, INCORPORATED, HUNTLEIGH USA CORPORATION, ICTS INTERNATIONAL NV, GLOBE

AVIATION SERVICES CORPORATION, BURNS INTERNATIONAL SECURITY SERVICES CORPORATION, PINKERTON'S INCORPORATED, BOEING COMPANY, AMEC, PLC, KABACK ENTERPRISES,

Defendants,

THE WTC PLAINTIFFS,

Plaintiff-Intervenor.

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UNITED STATES DISTRICT COURT
SOUTHERN DISTRICT OF NEW YORK

IN RE: SEPTEMBER 11 PROPERTY DAMAGE AND BUSINESS LOSS LITIGATION	21 MC 101 (AKH)
AEGIS INSURANCE SERVICES, INC., et al., Plaintiffs, -against- 7 WORLD TRADE CENTER COMPANY, L.P., et al., Defendants.	04 CV 7272 (AKH) **SUPPLEMENTAL AND AMENDED DECLARATION OF JOSE L. TORERO**

I, Jose L. Torero, declare:

1. I am the Director of the BRE Centre for Fire Safety Engineering at the University of Edinburgh. I was previously an Associate Professor, Fire Protection Engineering at the University of Maryland. I have authored 20 book chapters and more than 300 technical publications in a broad array of subjects associated with fire safety engineering. I was awarded the Arthur B. Guise Medal by the Society of Fire Protection Engineers in 2008 in recognition of eminent achievement in advancing the Science of Fire Protection. I am Chair of the Fire & Safety Working Group at the Council on Tall Buildings and Urban Habitat and Vice Chair of the International Association for Fire Safety Science. My curriculum vitae is attached hereto as Exhibit A.

2. I hold three academic degrees: (1) BEng. Pontificia Universidad Católica del Perú (1989); (2) M.S. University of California at Berkeley (1991); and (3) PhD. University of California at Berkeley (1992).

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3. In 2003 I was retained by counsel for plaintiffs in this litigation to serve as consulting fire protection engineer. I make this affidavit based upon the work that I have done in studying the factors that contributed to the total collapse of 7 World Trade Center (WTC7).

4. I have reviewed thousands of documents, drawings, and photographs, and actively participated in and reviewed the computer modeling performed on behalf of the plaintiffs in this case.

5. The opinions that follow are based on that review and activity, and are made to a reasonable degree of scientific probability. These opinions and the data and materials relied upon in forming these opinions are more fully set forth in my report dated February 12, 2010, attached hereto as Exhibit B and made a part hereof.

6. Based on my work to date, including computer modeling performed by me and my staff at the University of Edinburgh in which many columns were removed in the model to ascertain the effect on the structure of the building, it is my opinion that any structural damage caused by debris from the collapse of WTC1 or WTC2 played no part in the collapse of WTC7.

7. Based on my work to date, including computer modeling performed by me and my staff at the University of Edinburgh, it is my opinion that a diesel fuel fire occurred on September 11, 2001 on the fifth floor of WTC7 in the area of the transfer trusses. Such fires, fueled by between 7,350 and 9,300 gallons of diesel fuel from a leak in the Salomon Brothers' Standby Generator System, would have been of such high temperatures and lasted for such duration that they would have compromised the strength of the transfer trusses, caused their failure, and ultimately caused the failures of Columns 79 and/or 80 leading to a global collapse of WTC7.

8. Specifically, a diesel fuel fire in the fifth floor mechanical room would heat: (1) the members of Truss 2 that are fully immersed in the mechanical room, including Columns 77, 80, and the eastern diagonal of Truss 2; and (2) the members of Truss 1 immersed in the north wall of the mechanical room, though to a somewhat lesser degree.

9. The diesel fuel fire would have generated sufficiently high structural temperatures in the members of Truss 2 to cause them to lose strength and fail.

10. This failure of the eastern side of Truss 2 would have caused load redistribution towards Truss 1 and Column 79, which would overload these members. The east diagonal of Truss 1, which had the lowest factor of safety, would have likely failed first and resulted in the subsequent failure of Column 79. This was manifested visibly as the sinking of the East Penthouse.

11. The combined effect of the failure of the eastern side of Truss 2, Column 79 and the east diagonal of Truss 1, would have resulted in significant load transfer to Columns 73 and 74, as well as the core. This was manifested visibly as the "kink". As Columns 73 and 74 were not immersed in the mechanical room, and therefore not significantly heated, a delay was observed between the sinking of the penthouse and the subsequent "kink".

12. As described in the Second Declaration of Guy Nordenson, loss of the eastern region of the building's interior created a large area of laterally unbraced perimeter frame and activated the fracturing of the floor slabs at the western trench headers leading to global collapse.

I declare under penalty of perjury that the foregoing statements made by me are true. I am aware that if any of the foregoing statements made by me are willfully false, I may be subject to punishment.

JOSE L. TORERO

DATED: April 1, 2010

José L. Torero, FRSE

BRE Trust/RAEng Professor of Fire Safety Engineering
Director, BRE Centre for Fire Safety Engineering
Head, Institute for Infrastructure & Environment
The University of Edinburgh

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Education & Professional Accreditation

Chartered Engineer, Engineering Council Division, UK		(2002)
Ph.D.	University of California, Berkeley	(1992)
M.Sc.	University of California, Berkeley	(1991)
B.Sc.	Pontificia Universidad Catolica del Peru	(1988)

Academic Contributions

Authorship of a book in computational methods for fire safety engineering, more than 20 book chapters and more than 400 technical publications in a broad array of subjects associated to fire safety engineering.

Awards

Elected fellow of the Royal Society of Edinburgh and awarded the Arthur B. Guise Medal by the Society of Fire Protection Engineers (USA) in 2008, both in recognition of eminent achievement in advancing the Science of Fire Protection. Appointed to a Research Professorship by the Royal Academy of Engineering in 2004 which is the highest external appointment made by this institution. Received diverse scientific awards such as the NASA-Certificate of Recognition for Outstanding Contributions to Space Shuttle Mission and the Faculty Achievement Award, from the Office of the President of the University of Maryland. Recognised for service to the profession with honorary membership to the Salamander Fire Protection Engineering Honour Society and with the Faculty Service Award, A. J. Clark School of Engineering (University of Maryland). Acknowledged for oral communication with the William M. Carey Award for the Best Paper Presented at the Fire Suppression and Detection Research Application Symposium (2001) and for written communication with the Harry C. Bigglestone Award for the Best Paper Published in Fire Technology in 2002 and 2005, the Bodycote Warrington Fire Research Prize and the FM Global Best Paper Award both in 2007. He was awarded the Lord Ezra Award (2009) for innovation in Combustion Engineering by the Combustion Engineering Association, UK. In 2009 he also received the Best Knowledge Transfer Partnership Award of Scotland from the Scottish Executive. Teaching contributions have been recognised with the Lilly-Center for Teaching Excellence Fellowship, the Outstanding Mentor of the Year Award, the E. Robert Kent Outstanding Teaching Award for Junior Faculty and the Outstanding Teacher Award all at the University of Maryland. Prof. Torero's work bringing technology to the Fire Service was the subject of the April, 2007 BBC Horizon show: "*Skyscraper Fire Fighters*" that has been shown in more than 30 countries.

Academic Experience

Upon completion of doctoral studies and a brief Post Doctoral appointment at NASA Lewis Research Centre (1992), joined the Laboratoire de Chimie et Physique de la Combustion (Poitiers, France) as a European Space Agency Post Doctoral researcher (1993) followed by an appointment as a CNRS Research Scientist at the Laboratoire de Combustion et Detonique (Poitiers, France) until 1995. Directed research programmes in spacecraft fire safety, polyurethane foam fires, compartment fires and tunnel fire spread and smoke control. Placed experiments in 3 Space Shuttle Missions and two sounding rockets.

Joined the Department of Fire Protection Engineering at the University of Maryland (1995-2001) where held the titles of Assistant and Associate Professor and remains as Adjunct Professor. Served also as Affiliate Associate Professor in the Department of Aerospace Engineering. Taught all general and specialty classes in Fire Protection Engineering, continued research in spacecraft fire safety and compartment fires and extended experience to the areas of material flammability, fire suppression, smoke detection and oil spill control. Developed state of the art laboratory facilities and test methods and managed a research group that exceeded twenty people. Research funds in excess of $4 million where raised in this period.

Appointed Reader in Fire Dynamics (2001) and later BRE Trust/ RAEng Professor of Fire Safety Engineering and Director of the BRE Centre for Fire Safety Engineering at the University of Edinburgh (2004). Raised industrial funds for the endowment of two Professorial Chairs, the organization of the BRE

Centre for Fire Safety Engineering and state of the art laboratory facilities. Managed research funds in excess of £6 million obtained from government, research councils and industry. Developed a new undergraduate curriculum in Structural Fire Safety Engineering and transformed a reduced group of one permanent staff and one student into a research group of more than 45 members with 9 permanent academic staff. Developed research work in the areas of tunnel fire safety, structural behaviour in fire, material flammability, forest fires, post fire remediation and sensor driven emergency response. Appointed Head of the Institute for Infrastructure and Environment in 2008 (Department Chair). The Institute counts with 45 staff members (22 Academic) and more than 100 PhD students with an overall yearly research budget of more than £3 million.

Appointed to the Advisory Boards of WPI and Glasgow Caledonian University and Adjunct Professor at the University of Cantabria, Spain. Held short time appointments as Visiting professor at the University of Texas at Austin, the University of California San Diego, the University of Bremen (ZARM), Germany, the Catholic University of Santiago, Chile, the Instituto Nacional de Tecnica Aeroespacial (INTA), Spain and the Universities of Poitiers, Paris VI, Bourges, ENSTIB, Ecole de Mines de Saint Etienne, Ecole Polytechnique and Aix-Marseille in France.

Supervised more than 30 M.Sc., 5 completed Ph.D. and 8 current Ph.D. students. Developed numerous short courses taught around the world to professionals in fire investigation, fire safety engineering design, building control and the fire service.

Professional Involvement & Affiliations

Active membership in The Institution of Fire Engineers (IFE), American Society of Mechanical Engineers (ASME), American Institute of Aeronautics and Astronautics (AIAA), Combustion Institute, International Association for Fire Safety Science (IAFSS), Society of Fire Protection Engineers (SFPE) and the National Fire Protection Association (NFPA).

Associate Editor of Combustion Science and Technology and member of the Editorial Boards of Fire Technology Journal, Fire Safety Journal, Fire Science and Technology and Progress in Energy and Combustion Science. Colloquium Chair for the 30th and 31st Combustion Symposium and member of the Program Committee for the 8th and 9th International Symposium on Fire Safety Science. Advisor to the National Association for State Fire Marshals (USA), the Scottish Chief Fire Officers Forum, the Office of the Deputy Prime Minister and Vice-Chair of the International Association for Fire Safety Science (IAFSS). Member of the Forum of Chief Fire Officers of Scotland (SDAF) and of the CFOA Training Needs Analysis Gateway Review Group and co-Chair of the Fire safety Working Group of the International Committee on Tall Buildings and Urban Habitat (CTBUH). Member of the Society of Fire Protection Engineers, International Standards Development Committee, Underwriters Laboratory STP-162 Foams Fire Suppression Systems Committee, the American Institute of Aeronautics and Astronautics (AIAA) Micro-Gravity and Space Processes Technical Committee, the Committee of the British Section of the Combustion Institute and the American Society of Mechanical Engineers, K-11 Committee on Fire and Combustion.

Experience as a Consultant

Member of the Board of Directors of LPP Combustion, LLC (USA), Technical Director for the Building Research Establishment (UK) and for I-Risk (Germany), served as consultant to the Vice-President of Peru (Peru), ESSAC (Peru), DICTUC SA (Chile), IRSN, INERIS and La Police Scientifique de Lyon (France), DVS Risk Services GmbH (Germany), Lurgi Metallurgie GmbH (Germany), Rushbrook Consultants (UK), Ove Arup & Partners (UK), Powerwall (UK), Jacobs Engineering (UK) and Jacobs Babtie (USA), Exponent Inc. (USA), Combustion Science and Engineering (USA), NRC (USA), Packer Engineering (USA), Rolf Jensen and Associates, Inc. (USA), Whirlpool Corporation (USA), and to the World Bank.

Conducted work on prescriptive and performance based design, forensic fire investigation and product development. Conducted detailed structural response to fire, fire resistance evaluation, material selection, life safety analysis, smoke evacuation, detection and alarm design as well as standard and advanced fire suppression systems. Developed projects on transportation centres, hangars, trains and aircraft, industrial facilities, tunnels, high rise buildings, public assembly facilities and historic buildings. Used different codes and standards as well as a comprehensive array of analytical and numerical tools. Conducted third party reviews and supported fire service and building control in the approval process.

Participated in landmark projects like the NASA Space Shuttle Hangars in Florida, the 80 storey Heron Tower in London, the Clyde and Dartford Tunnel fire safety design, the investigations of the WTC 1, 2 and 7 collapses, the Madrid Windsor Tower Fire, the Texas City and Buncefield Explosions as well as the Ycua Bolanos supermarket fire. Currently involved in the safety analysis of several operating nuclear power plants and the decommissioning of others.

Appendix

Lecture Invitations

Invited Conference Lectures

1. J. L. Torero, "Laminar Diffusion Flames Established over a Flat Plate Burner under Micro-Gravity Conditions," *International Workshop on Short Term Experiments under Strongly Reduced Gravity Conditions*, Bremen, Germany, July 1994.
2. J. L. Torero, "Diffusion Flames in Micro-Gravity," *Meeting of the ESA Physical Sciences Working Group*, Berlin, Germany, April, 1995.
3. J. L. Torero, "Numerical Simulation of Flat Plate Ethane-Air Diffusion Flames and Experimental Validation at Different Gravity Levels," *9th European Symposium on Gravity Dependent Phenomena in Physical Sciences*, Berlin, May 1995.
4. J. L. Torero, "The Emmons Problem: Experimental Results and Progress Leading to a MiniTexus Experiment," *ESA-Sounding Rocket Experiments Workshop*, ESTEC, Noordwijk, The Netherlands, September 1998.
5. J. L. Torero, "Material Flammability and Fire Safety," *Society of Fire Protection Engineers*, Chesapeake Chapter, Maryland, September, 1998.
6. J. L. Torero, "La Formation de l'Ingenieur Incendie-Programmes Developpes aux Etats Unis et dans d'Autres Pays," *SFPE Chapitre Francaise*, Les Salons du Grand Louvre, October 1998.
7. J. L. Torero, "Educación en Ingeniería de Protección Contra Incendios," *Primer Foro Regional NFPA*, Lima '99, Lima, Peru, October, 1999.
8. J.L. Torero, "Challenges and Needs in Fire Protection Engineering Research and Education," *European Seminar on Environmental Risks*, Niort, France, October 2000. ***(Keynote)***
9. J.L. Torero, "Cooperation and Student Exchange Between the University of Maryland and French Higher Education Institutions," *Global E3 Annual Meeting*, Lake George, New York, June 2001. ***(Keynote)***
10. J.L. Torero, "The Mass Transfer Number as a Criterion for Spacecraft Material Flammability," *Workshop on Research Needs in Fire Safety for the Human Exploration and Utilization of Space*, NASA Glenn Research Center, Cleveland, Ohio, June 2001.
11. J.L. Torero, "The Role of Fire Science in Fire Investigation," *Fire Safety and Rescue Asia Conference*, Singapore, November, 2001. ***(Keynote)***
12. Torero, J. L., J. G. Quintiere and T. Steinhaus, "Fire Safety in High-rise Buildings: Lessons Learned from the WTC," 51st *Jahresfachtagung der Vereingung zur Forderrung des Deutschen Brandschutzez e. V.*, Dresden, Germany, 2002. ***(Keynote)***
13. J.L. Torero, "Fire and the Environment," *International Workshop on Environmental Risk Assessment*, Damascus, Syria, October, 2002. ***(Keynote)***
14. J.L. Torero, "Scaling of Micro-gravity Combustión Systems, Implications to Spacecraft Fire Safety" *European Workshop on Micro-gravity Combustion*, Poitiers, France, October 2002. ***(Keynote)***
15. J.L. Torero, "Desarrollo de una Reglamentacion Adecuada en Materia de Seguridad Contra Incendios," *Conference on Fire Safety organized by the Vice-President of the Republic*, Lima, Peru, November 2002. ***(Keynote)***
16. J.L. Torero, "Conclusiones para una Reglamentacion Adecuada en Materia de Seguridad Contra Incendios," *Conference on Fire Safety organized by the Vice-President of the Republic*, Lima, Peru, November 2002.
17. J.L. Torero, "Fire Safety Science in Support of Performance Based Design: Innovation or Just Filling the Gaps?," *The Graduate Lecture*, The Institution of Fire Engineers, Preston, Lancashire, April 2003. ***(Keynote)***
18. J.L. Torero, "Fire Modeling and Fire Performance," *The Rasbash Lecture and ECD Conference*, Ministry of Defence, Whitehall, London, UK, June 2003.
19. J.L. Torero, "La Experiencia del World Trade Center," *Seminario Donde Hubo Fuego, Que Hacemos con las Cenizas*, Santiago, Chile, June 2003. ***(Keynote)***

20. J.L. Torero, "L'Approche des Risques en Europe et aux Etats-Unis," *Colloque Les risques Industriels & Technologiques, Enjeux Internes et Effets Externes, Bourges*, France, October 2003. ***(Keynote)***

21. J.L. Torero and D.D. Drysdale, "Ignition and Flame Spread Studies as they Relate to Material Flammability," *Joint Meeting of the Fire Engineering Research Network (FERN) and the Fire Chemistry Network (FCHEM)*, March, 2004.

22. J.L. Torero, "FireGrid: Data Base Needs," *Digital Library Workshop*, National Institute of Standards and Technology (NIST), Maryland, USA, April 2004.

23. J.L. Torero, "Structures in Fire: An Overview of the Boundary Condition," *Fire And Structures: The Implications of the World Trade Center Disaster Conference*, The Royal Society of Edinburgh, Edinburgh, April, 2004.

24. J.L. Torero, "The Use and Misuse of Fire Modelling" *Society of Fire Protection Engineers*, California Chapter Spring Meeting, Luncheon Speaker, May, 2004.

25. J.L. Torero, "The Risk Imposed by Fire to Buildings and how to Address it," *NATO-Russia Workshop on the Protection of Civil Infrastructure from Acts of Terrorism*, Russian Academy of Sciences, May 2004.

26. J.L. Torero, and T. Steinhaus, "Applications of Computer Modelling to Fire Safety Design," 53rd *Jahresfachtagung der Vereingung zur Forderrung des Deutschen Brandschutzez e. V.*, Essen, Germany, June, 2004. ***(Keynote)***

27. J. L. Torero, "Lecciones Aprendidas Durante el Colapso de las Torres Gemelas en N.Y.," *Primer Congreso Nacional de Seguridad Contra Incendios, NFPA 2004*, Mexico City, November, 2004. ***(Keynote)***

28. J.L.Torero, "Introducción al Diseño Basado en el Desempeño de la Ingeniería Contra Incendios," *Primer Congreso Nacional de Seguridad Contra Incendios, NFPA 2004*, Mexico City, November, 2004.

29. J.L.Torero, "L'évolution du métier Préventeur – Fire Risk Manager" *Salon POLLUTEC*, Lyon, France, November 2004. ***(Keynote)***

30. J.L. Torero, "What is Fire Engineering? Where has it come from and where is it going?" *Developing the Role of Fire Engineering*, Cavendish Conference Centre, London, New Civil Engineering, April 2005.

31. J.L. Torero, "Structural Fire Engineering and Conjugate Heat Transfer," *Fire Bridges*, Belfast, Northern Ireland, May 2005.

32. J.L. Torero, "How can Fire Models Support Fire Reconstruction?" *The Rasbash Lecture and ECD Conference*, Ministry of Defense, Whitehall, London, UK, June 2005.

33. B. Lane, J.L. Torero, A. Usmani, S. Lamont, A. Jowsey, G. Flint, "Structural Fire Response and Collapse Analysis of WTC 1 & 2," *Technical Conference on the Federal Building and Fire Safety Investigation of the World Trade Center (WTC) Disaster*, National Institute of Standards and Technology, Gaithersburg, Maryland, September, 2005.

34. J.L. Torero, "Forensic Fire Investigation," *Fire Risk Management Networking Meeting*, IOSH, Edinburgh, September 2005.

35. J.L. Torero, "Fire-Arguably the Most Destructive Risk a Business Faces-Do We Understand this Risk? Are We Protected Adequately?" *AEOLUS*, Edinburgh, October, 2005.

36. J.L. Torero, "Heat and Mass Transfer in Fires: Scaling Laws and their Application" *12emes, Journees Internationales de Thermique*, Tangiers, Morocco, November 2005. ***(Keynote)***

37. J.L. Torero, "Structures and Fire – Modern Techniques in Building Design," *Institution of Engineers of Brazil*, Sao Paulo, Brazil , November 2005. ***(Keynote)***

38. J.L. Torero. "Smoke and Fire Detection," *Meeting of the GDR Feux*, ENSMA, Poitiers, January, 2006.

39. J.L. Torero "La Seguridad Contra Incendios en las Edificaciones: ¿Responsabilidad de Ingenieros o de Arquitectos? *International Conference to Celebrate the 10th Anniversary of the Polytechnic University of Puerto Rico*, Overcoming Fire: Architecture and Engineering Solutions, Puerto Rico, February 2006. ***(Keynote)***

40. J.L. Torero "The NIST Report: What are the Future Design Implication for High Rise Buildings," *Designing for Fires in the UK: Can we learn from the NIST Report?*, Institution of Civil Engineers, London, March 2006.

41. J.L. Torero "High Power Computing Solutions for Fire," National Science Foundation, *NSF Workshop on Cyber-based Combustion Science*, Washington D.C., USA, April 2006.
42. J.L. Torero "Questions Liées à la Formation et à l'Entraînement des Personnes Avant, Pendant et Après la Crise," *Stop Feux*, Marseille, May 2006.
43. J.L. Torero, "Post-Flashover Numerical Modelling," *FDS Global Seminar*, Ove Arup and Partners, London, May 2006.
44. J.L. Torero, "Métodos de Protección Pasiva, Análisis Critico y Tendencias," *Seminario de Innovación en el Diseño y Protección de Estructuras contra Incendios*, Santiago de Chile, July, 2006. ***(Keynote)***
45. J.L. Torero, "Emergency Response for Fires: Sensors, Fire Fighters or Both," *Royal Academy of Engineering Research Forum*, September 2006.
46. J.L. Torero, "Te Risk Imposed by Fire to Tall Buildings, What is the State of the Art?," *International Conference on Fire Safety in Tall Buildings*, Santander, October 2006. ***(Keynote)***
47. J.L. Torero, "Sensor Driven Emergency Response for Fires, FireGrid," *Distinguish Lecture Series in Mechanical Engineering, University of Texas at Austin*, October 2006.
48. J.L. Torero, "Fire Safety Engineering: Science or Regulation?" *IRSN Conference on Fire Research and Applications*, Lyon, France, December 2006. ***(Keynote)***
49. J. L. Torero, "Industrial Needs, New Regulation, Existing Knowledge and Available Training in Structural Fire Safety Engineering: Harmony or Chaos?" *IStructE-Seminars*, Royal Society of Edinburgh, Edinburgh, January 2007.
50. J.L. Torero, "Fire dynamics and Building Design," *Western Society of Engineers Annual Meeting*, Chicago, Illinois, USA, May 2007. ***(Keynote)***
51. J.L. Torero, "The Challenge of Interpreting Material Flammability Tests," 11th European meeting on Fire Retardant Polymers, Bolton, UK, July 2007. ***(Keynote)***
52. J.L. Torero, "How Does Academic Research Benefits Stakeholders in the Fire Engineering Disciplines," *Institution of Fire Engineers Annual General Meeting*, Extending the Boundaries of Fire Engineering, Cambridge, July 2007.
53. J.L. Torero, "Emergency Response Post-Terrorist Induced Fire: The Need for Physically based Support Tools," *NATO Advanced Research Workshop*, Urban Structures Resilience under Multi-Hazard Threats: Lessons of 9/11 and Research Issues for Future Work, Moscow, July 2007.
54. J.L. Torero, "Comportamiento Frente al Fuego de Materiales y Elementos de la Construcción," 2do Encuentro de la Asociación Latino-Americana de Laboratorios de Ensayos de Fuego," Buenos Aires, Argentina, August 2007. ***(Keynote)***
55. J.L. Torero, "Heat and Mass Transfer in Fires: Scaling Laws and their Application," *10th UK National Heat Transfer Conference*, Edinburgh, September 2007.
56. J.L. Torero, "Fire Prevention and Fire Suppression: What Makes Fire Different in Spacecraft," *Association of Space Explorers – The ASE Planetary Congress*, XX Congress, Edinburgh, UK, September 2007.
57. J.L. Torero, "Ingeniería de Protección Contra Incendios: Orden o Caos," *Segundo Congreso NFPA República Dominicana*, Santo Domingo, Dominican Republic, September 2007. ***(Keynote)***
58. J.L. Torero, "Structural Fire Engineering: A New Design Paradigm," SFPE Professional Development Conference and Exposition, Las Vegas, Nevada, USA, October 2007. ***(Keynote)***
59. J. L. Torero, "Role of Research In Supporting Developments in Fire Safety and Property protection," BRE Conference on Fire Safety, November, Garston, 2007. ***(Keynote)***
60. J.L. Torero, "Fundamentos de Ingeniería de Protección Contra Incendios," Instituto Nacional de Defensa Civil, February, Lima, Perú, 2008.
61. J.L. Torero, "The Dalmarnock Fire Tests: New Findings in High Rise Fire Safety," Chicago Commission on High Rise Buildings, Dinner Speaker, March 2008.
62. J.L. Torero, "Acciones a tomar por la empresa para prevenir riesgos y su papel en la sociedad para prevención," Prevención y Atención de Desastres en la Empresa Privada, Cámara de Comercio Peruano Británica, Lima, Perú, August 2008.

63. J.L. Torero, "Estrategias y Conceptos de Protección Contra Incendios: Instalaciones Contemporáneas y Futuras," 2nd Latin American Conference on Fire Protection Engineering, Lima, Peru, August 2008.

64. J. L. Torero, "Ingeniería de Protección Contra Incendios: Responsabilidad de Ingenieros o de Arquitectos," Buenos Aires International Security Exhibition & Conference, BISEC, August 2008.

65. J. L. Torero, "The Concepção de Prédios Altos (Arranha-Céus):O Comportamento de Estruturas ao Fogo,"10° Seminario "Tecnología de Estructuras: proyecto y producción con foco en la racionalización y calidad" SindusCon SP, Hotel Grand Hyatt, Sao Paulo, Brazil, August 2008.

66. J. L. Torero, "Fire Protection Engineering: Quo Vadis?" Arthur B. Guise Medal Lecture, Society of Fire Protection Engineers, Annual Meeting, Charlotte, North Carolina, October 2008. ***(Keynote)***

67. J. L. Torero, "Fire Investigation Beyond Cause and Origin," Chief Fire Officers Association – Scotland, Conference on Forensic Fire Engineering, Glasgow, November 2008.

68. J. L. Torero, "High Stakes and High Rise Fire Safety: Building Design and Fire Liability," Defence Research Institute, Fire and Casualty Seminar, Marriott Chicago Downtown, Chicago, Illinois, USA, November 2008.

Invited Talks

1. J. L. Torero, "The Effect of Buoyancy on the Geometry of Laminar Diffusion Flames Established Over a Flat Plate Burner," Borwn Bag Seminar Series, Department of Mechanical Engineering, *The University of Texas at Austin*, Texas, U.S.A., February, 1995.

2. J. L. Torero, "Buoyancy Effects on Smoldering of Polyurethane Foam," BFRL Lecture Series, National Institute of Standards and Technology, Gaithersburg, Maryland, U.S.A. December, 1995.

3. J. L. Torero, "The Role of Micro-Gravity Experiments on Spacecraft Fire Safety," Serie Annual de Conferencias, Escuela Tecnica Superior de Ingenieros Aeronauticos, Madrid, Spain, January, 1998.

4. J. L. Torero, *Material Flammability Studies for Micro-Gravity Environments*, BFRL Lecture Series, National Institute of Standards and Technology, Gaithersburg, Maryland, U.S.A., October 1998.

5. J. L. Torero, "Seguridad Contra-Incendios en Naves Espaciales - Combustion en Micro-Gravedad," Serie de Conferencias Distinguidas de la Escuela de Ingenieros, *Pontificia Universidad Catolica de Chile*, Santiago, Chile, November 1998.

6. J. L. Torero, "Combustion et Securite d'Incendie," Seminaire du LCD, *Ecole National Superieure de Mecanique de d'Aerotechnique*, Poitiers, France, February, 1999.

7. J. L. Torero, "Energy Release Rate: Determination and Application," Danish Technical University, March, 2000.

8. J.L. Torero, "Flammability Criteria Relevant to Material Selection for Spacecraft Applications" Department of Mechanical and Aerospace Engineering Combustion Seminar Series, Princeton University, April, 2000.

9. J.L. Torero, "Ignition Signatures of a Smolder Reaction in Polyurethane Foam," IUSTI Marseille, France, July 2000.

10. J.L. Torero, "Fire Protection Engineering: Current Accomplishments and Challenges," Ecole National Superieure des Mines de Saint-Etienne, Saint-Etienne, November, 2000.

11. J.L. Torero, "Material Flammability, The Screening of Complex Materials for Complex Applications: The International Space Station," Distinguished Lecture Series in Thermofluid Mechanics, Department of Mechanical Engineering, Purdue University, West-Lafayette, Indiana, March 2001.

12. J.L. Torero, "Material Flammability Assessment for the International Space Station," Union College, Schenectady, New York, April, 2001.

13. J.L. Torero, "El World Trade Center: Algunas Preguntas," Serie de Conferencias Distinguidas de la Escuela de Ingenieros, Pontificia Universidad Catolica de Chile, April 2002.

14. J.L. Torero, "Fire Safety Engineering after September 11th, 2001," Herriot-Watt University, Edinburgh, November 2002.

15. J.L. Torero, "A Case for the Use of the Mass Transfer Number as a Flammability Criterion," Factory Mutual Global, Massachusetts, USA, June 2003.

16. J.L. Torero, "The Role of Fire Safety Engineering in Fire Reconstruction: A Case Study – WTC 1&2," Department of Physics Distinguished Lecture Series, University of Bergen, Norway, September 2003.
17. J.L. Torero, "The Use of Fire Safety Engineering in the WTC Investigation," Stord-Haugesund College, Norway, September 2003.
18. J. L. Torero, "Specialized Studies in Fire Safety Engineering," Packer Engineering, Chicago, March 2004.
19. J.L. Torero, "Fire Safety Engineering Analysis of the WTC Collapse," SFPE Norwegian Chapter, Stord-Haugesund College, Norway, March 2004.
20. J.L. Torero, "The Use of the Mass Transfer Number as a Flammability Criterion for Micro-Gravity Environments," Lecture Series of the Mechanical and Aerospace Engineering Department, University of California, San Diego, May, 2004.
21. J.L. Torero, "Ingenieria de Proteccion Contra Incendios Despues del 11 de Septiembre del 2001," Pontificia Universidad Catolica de Chile, Septembre 2004.
22. J.L. Torero, "Comportamiento al Fuego de Estructuras en Madera," Pontificia Universidad Catolica de Chile, June 2005.
23. J.L. Torero, "Tecnicas Modernas de Ingenieria de Proteccion Contra Incendios," Pontificia Universidad Catolica del Peru, November 2005.
24. J.L. Torero, "Fire Safety Engineering in Modern Cities – Design, Prevention and Response," Joint Meeting of the Fire Brigades, Sao Paulo, Brazil, November 2005.
25. J.L. Torero, "Fire and Combustion," Pontificia Universidad Catolica, Rio de Janeiro, Brazil, November 2005.
26. J.L. Torero, "FDS: The Good, the Bad and the Ugly," L'Institut de Radioprotection et Sûreté Nucléaire, Cadarache, France, February 2006.
27. J.L. Torero, "Smoke Properties Affecting Fire Detection," L'Institut de Radioprotection et Sûreté Nucléaire, Cadarache, France, February 2006.
28. J.L. Torero, "Fire problems for which we can not solve the Maths," School of Mathematics Colloquium Series, May 2006.
29. J. L. Torero, "Emergency Response Assisted by Data," Heriot Watt University, November 2006.
30. J.L. Torero, "Sensor Driven Emergency Response: FireGRID," University of Ghent, March 2007.
31. J. L. Torero, "Modelling of Cone Calorimeter Behaviour," Predicting the Fire behaviour of Nano-Composites, Bolton, UK, July 2007.
32. J.L. Torero, "Fire Investigation Beyond NFPA 921," Packer Engineering Inc., Naperville, Illinois, USA, July 2007.
33. J.L. Torero, "Ingeniería de Protección Contra Incendios Más Allá de las Pruebas Estándar y la Regulación," 2do Encuentro de la Asociación Latino-Americana de Laboratorios de Ensayos de Fuego," Buenos Aires, Argentina, August 2007.
34. J.L. Torero, "Análisis de la Protección Contra Incendios de un Túnel: El Caso del Túnel de Dartford," 2do Encuentro de la Asociación Latino-Americana de Laboratorios de Ensayos de Fuego," Buenos Aires, Argentina, August 2007.
35. J.L. Torero, "Modern Methods in Fire and Explosion Investigation," Pressure Release, Fires and Explosions, Thermofluid Modelling and Simulation, IMechE, London October 2007.
36. J.L. Torero, "Materiales de Construcción y la Protección Industrial," 7mo Seminario de Ingeniería de Protección Contra Incendios, Santiago, Chile, October 2007.
37. J. L. Torero, "Fire Research at the University of Edinburgh, An Overview," Seminar on the Japanese Center of Excellence for Fire Safety Science and Developing a Global Fire Research Network, Kingston University, London, UK, December 2007.
38. J.L. Torero, "Modern Methods in Fire and Explosions Investigation," Fire Service Fire Investigation Forum, Edinburgh, January 2008.
39. J. L. Torero, "Sistemas de Alarma y Detección de Incendios en Terminales Aéreos," Seminario de Medio Ambiente y Salud Ocupacional, Lima Airport Partners, June, 2008.

40. J. L. Torero, "Sistemas de Control y Extinción de Incendios en Aeronaves Comerciales," Seminario de Medio Ambiente y Salud Ocupacional, Lima Airport Partners, June, 2008.
41. J. L. Torero, "Seguridad contra incendios en las edificaciones modernas," Universidad Peruana de Ciencias Aplicadas, June 2008.
42. J.L. Torero, "Conceptos de Protección Contra Incendio en Túneles e Instalaciones Subterráneas," 2nd Latin American Conference on Fire Protection Engineering, Lima, Peru, August 2008.
43. J.L. Torero, "Comportamiento de las Estructuras durante un Incendio," 2nd Latin American Conference on Fire Protection Engineering, Lima, Peru, August 2008.
44. J.L. Torero, "INDECI: Exigencias e Implementación de la Protección Contra Incendios," 2nd Latin American Conference on Fire Protection Engineering, Lima, Peru, August 2008.
45. J. L. Torero, "Edificios Complejos, Método Normativo o Diseño a base de Desempeño," Buenos Aires International Security Exhibition & Conference, BISEC, August 2008.
46. J. L. Torero, "WTC Have Lessons Been Learnt?"Institution of Civil Engineers, Graduates and Students Committee, The University of Edinburgh, October 2008.

Publications

Books

1. Alvear, D. Capote, J.A., M. Lazaro, Abreu, O.V., Rein, G. and Torero, J.L. "Modelado y Simulación Computacional en la Edificación," Díaz de Santos Eds., pp. 336, 2007.

Chapters in Books

1. H.Y. Wang, J.L. Torero, L. Bonneau and P. Joulain, "Numerical Simulation of Ethane-Air Diffusion Flames Established over a Flat Plate Burner: Comparison with Different Gravity Experiments," *Transport Phenomena in Combustion,* S.H. Chan Editor, **2**, Taylor and Francis Publishers, 1141-1152, 1996.
2. J. L. Torero, H. Y. Wang, P. Joulain and J. M. Most "Flat Plate Diffusion Flames: Numerical Simulation and Experimental Validation for Different Gravity Levels," *Lecture Notes in Physics*, Ratke, L. Walter, H. and Feuerbacher, Eds., Springer-Verlag, **464**, 401-408, 1996.*(Invited & Refereed)*
3. J. T'ien, H-Y. Shih, C-B. Jiang, H.D. Ross, F.J. Miller, A.C. Fernandez-Pello, J.L. Torero and D. C. Walther, "Mechanisms of Flame Spread and Smolder Wave propagation," Fire in Free Fall: Micro-Gravity Combustion, H. Ross, Editor, Academic Press Chapter 5, pp.299-418, 2001.
4. J.L. Torero, "The Risk Imposed by Fire to Buildings and how to Address it," The Protection of Civil Infrastructure from Acts of Terrorism, NATO Advanced Science Institute series, Kluwer Academic Publishers, Frolov and Becker Eds. Pp. 37-56, 2006.
5. C. Lautenberger, J.L. Torero and A.C. Fernandez-Pello, "Considerations for Material Flammability," Chapter 2, *Flammablity Testing of Materials in Building, Construction, Transport and Mining Sectors,* Apte Editor, Chapter 1, 1-21, 2006.
6. A. Jowsey, S. Welch and J.L. Torero, "Heat and Mass Transfer for Modeling of Structures in Fire," Transport Phenomena in Fire, B. Sunden and M. Faghri Editors, WIT Press, UK, Chapter 4, 2007.
7. J.L. Torero and R. Carvel, "The Dalmarnock Fire Tests: Preface," The Dalmarnock Fire Tests, Rein, Empis & Carvel Eds., 2-6, 2007.
8. S. Welch, A.S. Usmani, R. Upadhyay, D. Berry, S. Potter, J.L. Torero, "Introduction to FireGrid," The Dalmarnock Fire Tests, Rein, Empis & Carvel Eds., 7-30, 2007.
9. C. Abecassis Empis, A. Cowlard, S. Welch and J.L. Torero, "Test One: The Uncontrolled Fire," The Dalmarnock Fire Tests, Rein, Empis & Carvel Eds., 64-82, 2007.
10. A. Cowlard, T. Steinhaus, C. Abecassis Empis and J.L. Torero, "Test Two: The Controlled Fire," The Dalmarnock Fire Tests, Rein, Empis & Carvel Eds., 83-96, 2007.
11. A. Jowsey, J.L. Torero and B. Lane, "Heat Transfer to the Structure During the Fire," The Dalmarnock Fire Tests, Rein, Empis & Carvel Eds., 139-148, 2007.
12. G. Rein, J.L. Torero, W. Jahn, J. Stern-Gottfried, N.L. Ryder, S. Desanghere, M. Lazaro, F. Mowrer, A. Coles, D. Joyeux, D. Alvear, J.A. Capote, A. Jowsey, P. Reszka, "A Priori Modelling of Fire Test One," The Dalmarnock Fire Tests, Rein, Empis & Carvel Eds., 173-195, 2007.
13. W. Jahn, G. Rein and J. L. Torero, "A Posteriori Modelling of Fire Test One," The Dalmarnock Fire Tests, Rein, Empis & Carvel Eds., 196-114, 2007.
14. J.L.Torero, "Flaming Ignition of Solids Fuels," SFPE Handbook of Fire Protection Engineering, 4th Edition, Chapter 2-11, pp. 2-260-2-277, 2008.
15. Jowsey, A., Torero, J.L., Usmani, A. S., Lane, B. and Lamont, S., "Structural fire Design of Tall Buildings in Fire," *Fire Safety in High Rise Buildings*, VDM Publishing, 2009.
16. Capote, J.A., Alvear, D., Lazaro, M., Espina, P., Fletcher, I., Welch, S. and Torero, J.L., "Analysis of Thermal Fields Generated by natural Fires on the structural elements of Tall Buildings," *Fire Safety in High Rise Buildings*, VDM Publishing, 2009.
17. Amundarain, A., Torero, J.L., Usmani, A.S., Al-Remal, A.M., "Light Steel Framing in Fire: Challenges for a New Technology," *Fire Safety in High Rise Buildings*, VDM Publishing, 2009.
18. Usmani, A.S., Flint, G., Jowsey, A., Roben, C. and Torero, J.L., "Collapse Scenarios of WTC 1 & 2 with Extension to Generic Tall Buildings," *Fire Safety in High Rise Buildings*, VDM Publishing, 2009.

19. J.L. Torero, "The Risk Imposed by Fire to High Rise Buildings, Introduction," *Fire Safety in High Rise Buildings*, VDM Publishing, 2009.
20. J.L. Torero and G. Rein, "Physical parameters affecting Fire Growth," *Fire Retardancy of Polymeric Materials*, Taylor and Francis, Wilke & Morgan Editors, Chapter 3, pp. 43-74, 2010.
21. S. Welch, J.L. Torero and S. Paul, "Modelling of Fire Growth and Toxic Gas Formation," Fire Toxicity, Hull and Steck Editors, *(in Press)*, 2010.

Articles in Refereed Journals

1. J. L. Torero, M. Kitano and A. C. Fernandez-Pello, "Opposed Flow Smoldering of Polyurethane Foam," *Combustion Science and Technology*, **91** (1-3), 95-117, 1993.
2. J. L. Torero, A. C. Fernandez-Pello and D. Urban "Experimental Observations of the Effect of gravity Changes on Smoldering Combustion, " *AIAA Journal*, **31** (5), 991-996, 1994.
3. J.L. Torero, L.Bonneau, J.M.Most and P.Joulain "The Effect of Gravity on a Laminar Diffusion Flame established over a Horizontal Flat Plate," *Proceedings of the Combustion Institute*, **25**, 1701-1709, 1994.
4. J. L. Torero, A.C.Fernandez-Pello and M.Kitano "Downward Smolder of Polyurethane Foam," *Fourth International Symposium on Fire Safety Science*, 409-420, 1994.
5. X. Zhou, J. L. Torero, J. C. Goudeau and B. Bregeon "On the Ignition and Propagation of a Reaction Front Through a Porous Fuel: Application to Mixtures Characteristic of Urban Waste," *Combustion Science and Technology*, **110-111** (1-6), 123-146, 1995.
6. J. L. Torero and A. C. Fernandez-Pello "Natural Convection Smolder of Polyurethane Foam, Upward Propagation," *Fire Safety Journal*, **24** (1), 35-52, 1995.
7. L. Audouin, G. Kolb, J. L. Torero and J. M. Most "Average Centerline Temperatures of a Buoyant Pool Fire Obtained by Image Processing of Video Recordings," *Fire Safety Journal*, **24** (2), 167-187, 1995.
8. J. L. Torero, L. Bonneau, J. M. Most and P. Joulain "On the Geometry of Laminar Diffusion Flames Established over a Flat Plate Burner," *Advances in Space Research*, **16** (7), 149-152, 1995.
9. L. Audouin, G. Kolb, J.L. Torero and J.M. Most "Response to the Letter by D.Milov Commenting the Paper Entitled: "Average Centerline Temperatures of a Buoyant Pool Fire Obtained by Image Processing of Video Recordings" (F.S.J., 24, 2, 1995)," *Fire Safety Journal*, **24** (4), 361-363, 1995.
10. D. P. Stocker, S. L. Olson, D. Urban, J.L. Torero, D. Walther and A.C. Fernandez-Pello,"Small Scale Smoldering Combustion Experiments in Microgravity," *Proceedings of the Combustion Institute*, **26**, 1361-1368, 1996.
11. N. Wu, M. Baker, G. Kolb and J. L. Torero "Ignition, Flame Spread and Mass Burning Characteristics of Liquid Fuels on a Water Bed," *Spill Science and Technology Bulletin*, **3** (4), 209-213, 1996.
12. J. L. Torero and A. C. Fernandez-Pello "Forward Smoldering of Polyurethane Foam in a Forced Air Flow," *Combustion and Flame*, **106** (1-2), 89-109, 1996.
13. L. Brahmi, T. Vietoris, P. Joulain and J. L. Torero, "Experimental Study on the Stability of a Diffusion Flame Established in a Laminar Boundary Layer," *Microgravity Abstracts*, **5**, 80-87, 1998. *(in Japanese)*
14. L. Brahmi, T. Vietoris, J. L. Torero and P. Joulain, "Determination par camera Infrarouge des distributions de Temperature sur l'Enveloppe d'une Flamme de Diffusion Etablie sur un Bruleur Poreux Plan en Microgravite," *Enthropie*, **215**, 69-73, 1998. *(in French)*
15. N. Wu, G. Kolb and J. L. Torero, "Piloted Ignition of a Slick of Oil on a Water Sublayer: The Effect of Weathering," *Proceedings of the Combustion Institute*, **27**, 2783-2790, 1998.
16. T. Vietoris, J. L. Torero and P. Joulain, "Experimental Characterization of a Laminar Diffusion Flame in Micro-Gravity," *Journal de Chimie Physique*, **96**, 1022-1030, 1999.
17. J. P. Garo, J. P. Vantelon, S. Gandhi and J. L. Torero "Determination of the Thermal Efficiency Pre-boilover Burning of a Slick of Oil on Water," *Spill Science and Technology Bulletin*, **5** (2), 141-151, 1999.
18. L. Brahmi, T. Vietoris, J. L. Torero and P. Joulain, "Estimation of Boundary Layer Diffusion Flame Temperatures by Means of an Infra-Red Camera under Micro-Gravity Conditions," *Measurement Science and Technology*, **10**, 859-865, 1999.

19. R. T. Long, J. L. Torero, J. G. Quintiere and A. C. Fernandez-Pello, "Scale and Transport Considerations on Piloted Ignition of PMMA," *Sixth International Symposium on Fire Safety Science*, 567-578, 1999.

20. H. Y. Wang, J. L. Torero and P. Joulain, "Calculation of Vertical Parallel Wall Fires with Buoyancy Induced Flow," *Sixth International Symposium on Fire Safety Science*, 671-678, 1999.

21. T. Vietoris, P. Joulain and J. L. Torero "Experimental Observations on the Geometry and Stability of a Laminar Diffusion Flame in Micro-Gravity," *Sixth International Symposium on Fire Safety Science*, 373-386, 1999.

22. S. Leach, G. Rein, J. Ellzey, O. A. Ezekoye and J. L. Torero, "Kinetic and Fuel Property Effects on Forward Smoldering Combustion," *Combustion and Flame*, **120**, 3, 346-358, 2000.

23. M. K. Anderson, R. T. Sleight and J. L. Torero, "Ignition Signatures of a Downward Smolder Reaction," *Experimental Thermal and Fluid Science*, **21**,1-3, 33-40, 2000.

24. M. Anderson, R. Sleight and J. L. Torero "Downward Smolder of Polyurethane Foam: Ignition Signatures," *Fire Safety Journal*, **35**, 131-148, 2000.

25. Fernandez-Pello, A.C., Walther, D.C., Cordova, J.L., Steinhaus, T., Quintiere, J.G., Torero, J.L., and Ross, H., "Test Method for Ranking Materials Flammability in Reduced Gravity," *Space Forum*, **6**, 237-243, 2000.

26. T. Vietoris, J. L. Ellzey, P.Joulain, S.N. Mehta and J.L. Torero, "Laminar Diffusion Flame in Micro-Gravity: The Results of the Mini-Texus 6 Sounding Rocket Experiment, *Proceedings of the Combustion Institute*, **28**, 2000.

27. N. Wu, G. Kolb and J. L. Torero, "The Effect of Weathering on the Flammability of a Slick of Crude Oil on a Water Bed," *Combustion Science and Technology*, **161**, 269-308, 2000.

28. M. Roslon, S. Olenick, D. Walther, J.L. Torero, A.C. Fernandez-Pello and H. Ross, "Micro-Gravity Ignition Delay of Solid Fuels," *AIAA-Journal*,.**39**, No.12, pp. 2336-2342, Dec. 2001.

29. J.L. Cordova, D. C. Walther, J. L. Torero and A.C. Fernandez-Pello, "Oxidizer Flow Effects on the Flammability of Solid Combustibles," *Combustion Science and Technology*, **164**, N0. 1-6, pp. 253-278, 2001.

30. T. Vietoris , P. Joulain and J. L. Torero, "Gas-Gas and Gas-Solid Laminar Flat Plate Diffusion Flames in Micro-Gravity: Structure and Stability," *Micro-Gravity Science and Technology*, **XIII**, 1, 3-7, 2001.

31. C. Worrell, G. Gaines, R. Roby, L. Streit and J.L. Torero, "Enhanced Deposition, Acoustic Agglomeration and Chladni Figures in Smoke Detectors," *Fire Technology*, Fourth Quarter, **37**, Number 4, pages 343-363, 2001.

32. S.D. Wolin, N.L. Ryder, F. Leprince, J.A. Milke, F.W. Mowrer and J.L. Torero, "Measurements of Smoke Characteristics in HVAC Ducts," *Fire Technology*, Fourth Quarter, **37**, Number 4, pages 363-395, 2001.

33. Torero, J.L., Vietoris, T., Legros, G., Joulain, P. "Evaluation d'un Nombre de Transfert de Masse Réel d'une Flamme Ascendante" *Journal de Physique IV*, **11**, pp. 291-300, 2001. *(in French)*

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36. Rouvreau, S., Cordeiro, P., Joulain, P., Wang, H.Y. and Torero, J.L., "Numerical Evaluation of the Influence of Fuel Generation on the Geometry of a Diffusion Flame: Implications to Micro-Gravity Fire Safety," *Seventh International Symposium on Fire Safety Science*, 283-295, 2002.

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39. Rogaume, T., Jabouille, F., Auzanneau, M., Goudeau, J.C. and Torero, J.L., "The Effects of Different Airflows on the Formation of Pollutants During Waste Incineration," *Fuel*, **81**, 2277-2288, 2002.

40. G. Rein Soto-Yarritu, J.L. Torero and J.L. Ellzey, "Simulacion Numerica de Combustión Latente en Flujo Directo," *Revista Internacional de Métodos Numéricos para Cálculo y Diseño en Ingenieria*, **18**, No. 4, 459-474, December 2002. *(In Spanish)*

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Extension Activities and Professional Courses

1. *Fire Phenomena/Enclosure Fires* – Bureau of Alcohol Tobacco and Firearms, Maryland Fire and Rescue Institute, University of Maryland, August 1998.
2. *Control de Riesgos de Incendio* – Pontificia Universidad Catolica de Chile, Santiago, Chile, November 1998.
3. *Feu et Combustion* – Ecole National Superieure de Mecanique et d'Aerothechnique (ENSMA), Universite de Poitiers, France, March 1999.
4. *Seminaire sur le Management des risques d'Incedie*, Univeriste de Poitiers-Site de Niort, France, January, 2000.
5. *Fire Phenomena/Enclosure Fires* – Bureau of Alcohol Tobacco and Firearms, Maryland Fire and Rescue Institute, University of Maryland, August 2000.
6. *Fire Safety* – Masters of Science Loss Prevention and Risk Management, ENSI-Bourges, Bourges, France, November 2000.
7. *Fire Safety* – Masters of Science Loss Prevention and Risk Management, ENSI-Bourges, Bourges, France, December 2001.
8. *Fire Safety Engineering* – Ecole des Mines St. Etienne, St. Etienne, France, January, 2002.
9. *Fire Science and Fire Investigation* – The University of Edinburgh, April 2002.
10. *Performance Based Design of Fire Safety Systems* – Pontificia Universidad Catolica de Chile, June 2002.
11. *Introduction to Fire Safety Engineering,* – Ecole des Mines St. Etienne, St. Etienne, France, February, 2003.
12. *Fire Science and Fire Investigation* – The University of Edinburgh, March 2003.
13. *Fire Dynamics and Fire Safety Engineering Design* - The University of Edinburgh, March 2003.
14. *Ingenieria de Proteccion Contra el Fuego* - Pontificia Universidad Catolica de Chile, June 2003.
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17. *Concrete Structures in Fire* – Pontificia Universidad Catolica de Chile, September, 2004.
18. *Introduction to Fire Safety Engineering,* – Ecole Polytechnique de Marseille, Marseille, France, September, 2004.
19. *Introduction to Fire Safety Engineering,* – Ecole des Mines St. Etienne, St. Etienne, France, February, 2005.
20. *Timber Construction in Fire*– Pontificia Universidad Catolica de Chile, June 2005.
21. *Primer Seminario de Ingenieria de Proteccion Contra Incendios* – Pontificia Universidad Catolica del Peru, November 2005.
22. *Fire Dynamics and Fire Safety Engineering Design* - The University of Edinburgh, April 2006.
23. *Fire Science and Fire Investigation* – The University of Edinburgh, April 2006.
24. *Seminario de Innovación en el Diseño y Protección de Estructuras contra Incendios*, Santiago de Chile, July, 2006.
25. *Introduction to Fire Safety Engineering,* Ecole Polytechnique de Marseille, November 2006.
26. *Fire Science and Fire Investigation* – The University of Edinburgh, April 2007.
27. *7mo Seminario de Ingeniería de Protección Contra Incendios,* Santiago, Chile October, 2007.
28. *The Dalmarnock Fire Test-1st FireSEAT,* The University of Edinburgh, November 2007.
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Analysis of the Impact of a Fire in the Mechanical Room (5th & 6th Floor) of the World Trade Center 7 Building

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The University of Edinburgh
United Kingdom

February 12, 2010

Summary

Based on the results of my study, it is my opinion that a diesel fuel fire in the Mechanical Room would lead to the following collapse sequence:[i]

- The diesel fuel fire, having originated in the north-east quadrant of the 5th floor, spread to the Mechanical Room and heated the east side of Trusses 1 and 2 and the structural elements that join them. Such north-east quadrant fire also heated Column 79.

- If the epicentre of the fire was in the Mechanical Room, the east side of Truss 2, subjected to greater heating, would lose strength gradually redistributing the load mainly towards Truss 1 and Column 79.

- In this scenario, load redistributed from the east side of Truss 2 would result in the eventual failure of Column 79 followed by the failure of the east diagonal of Truss 1, manifested visibly as the sinking of the East Penthouse.

- If the epicentre of the fire was in the vicinity of Column 79, such column, subject to greater heating, would lose strength gradually redistributing the load mainly towards the east side of Trusses 1 and 2, also weakened by the heating.

- In that scenario, load redistributed from failing Column 79 would result in the overloading of weakened Trusses 1 and 2, especially their eastern columns and diagonals, causing their eventual failure. Again, manifested visibly as the sinking of the East Penthouse.

- The effect of the failure of the east side of Truss 2, Column 79 and the east diagonal of Truss 1 resulted in significant load transfer to Columns 73 and 74 as well as the core. Their failure is manifested visibly as the "kink."

- As described in [the GNA Global Collapse Report], this loss of the eastern region of the building's interior created a large area of laterally unbraced perimeter frame and activated the disintegration of the floor slabs at the western trench headers leading to the global collapse of WTC-7.

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[i] This opinion, and all opinions stated in this report are expressed to a reasonable degree of scientific probability.

Table of Contents

1. The Mechanical Room

The mechanical room was a two storey compartment located in the 5^{th} and 6^{th} floors of the World Trade Center Building as shown on the schematic in Figure 1 (blue area). This compartment was connected to a plenum on the East side and to a staircase on the West side.

Several important structural elements resided within the compartment. Details of the 5^{th} and 6^{th} Floor structural drawings (Figure 2(a) and Figure 2(b)) show that Columns 77, 80 and E4 were immersed within this room. These columns are marked in red.

The three columns immersed within the Mechanical Room were part of two major transfer trusses described in Figure 3 and Figure 4. The other three columns associated to those trusses (73, 74 and E3) were outside the mechanical room. These columns are shown in green in Figure 2.

As shown in Figure 3, the columns were linked by horizontal and diagonal structural elements, some of which were fully immersed in the Mechanical Room, some of which were partially immersed, and some of which remained outside the Mechanical Room. Figure 4 indicates in red the region that was within the Mechanical Room and in green those zones outside the Mechanical Room.

Truss 1 was adjacent to the north boundary wall of the Mechanical Room, partially immersed in a concrete block wall. It seems likely then that the concrete block wall would have been built up around the diagonal with the blocks omitted where the truss diagonal was located. There was also a 5/8" gypsum board on the outside of the wall which would have run continuously past the brace location.

A fire within the Mechanical Room heated Columns 77 and 80 and the non-vertical elements of Truss 2 which are shown red in Figure 4(a). The element E4 of Truss 1 was fully heated and all the non-vertical elements shown red in Figure 4(b)) partially heated due to the protection and heat sink provided by the north wall. This will be discussed in more detail later in the report.

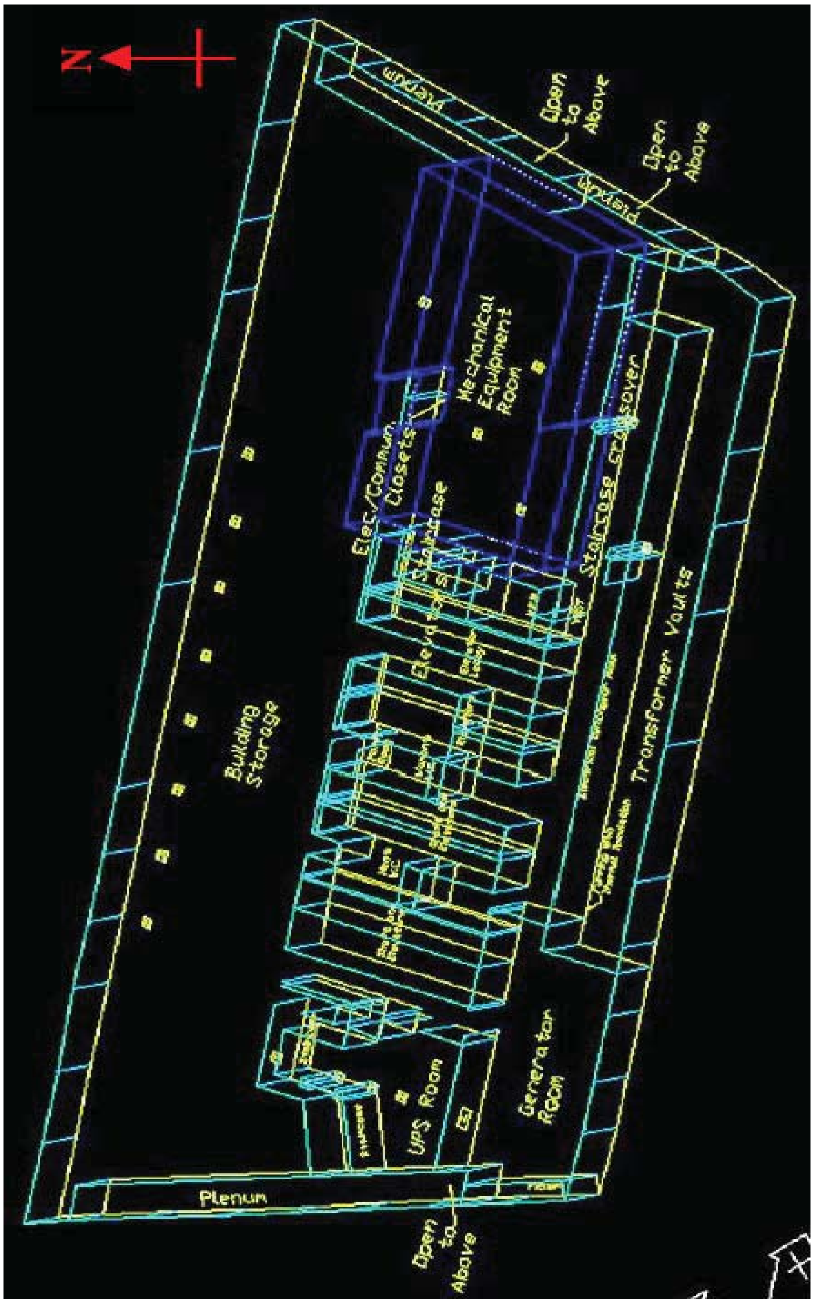
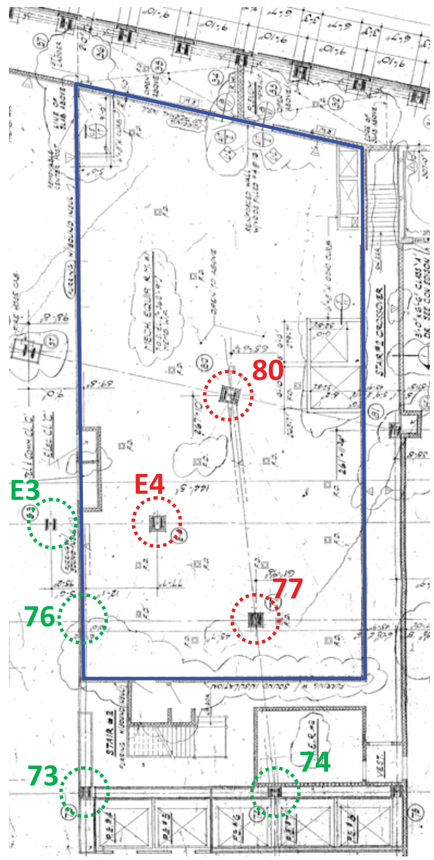
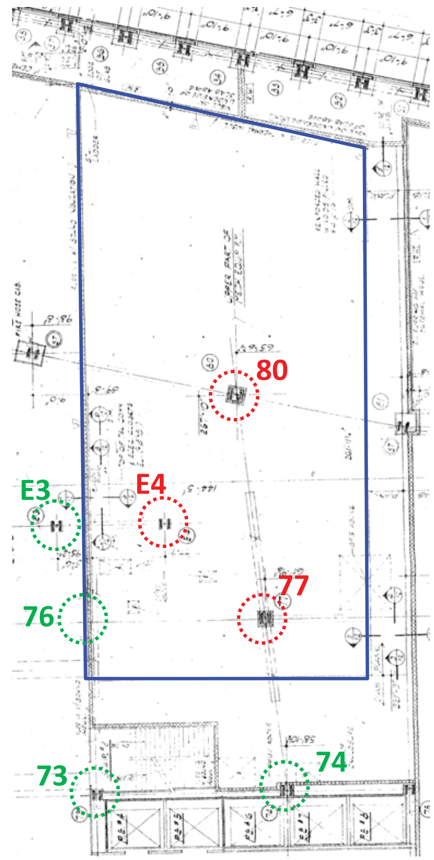


Figure 1 - *Schematic of the 5th and 6th floor configuration.*

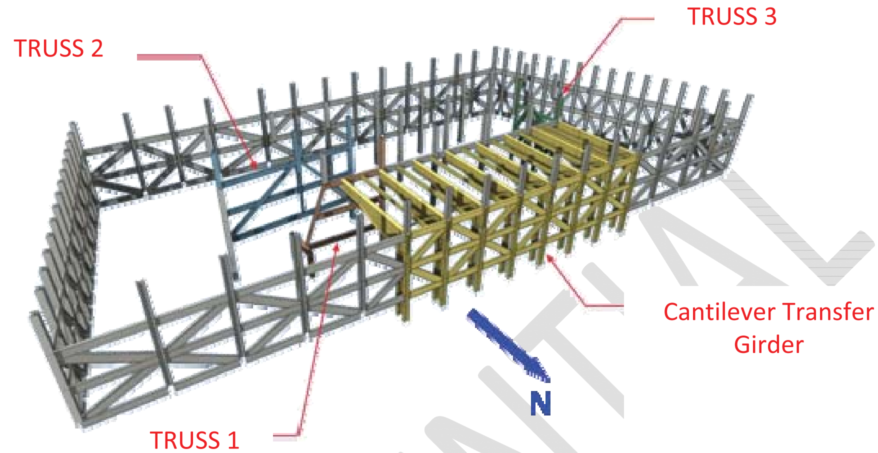


(a)

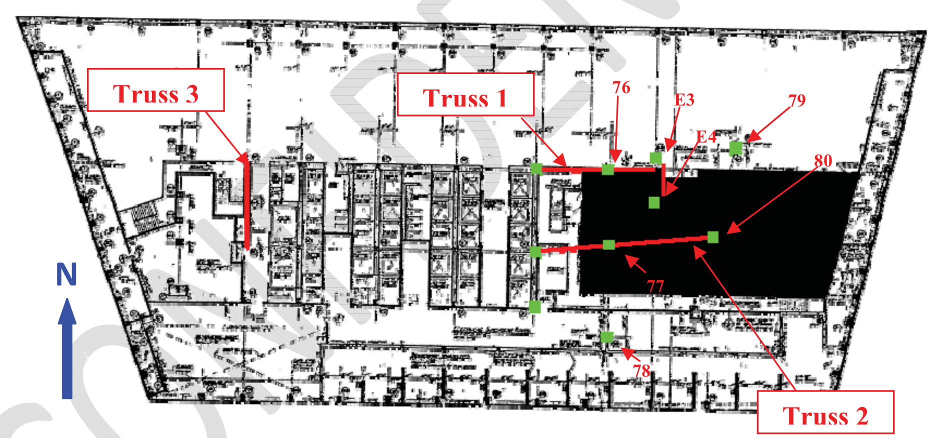


(b)

Figure 2 - *Detail of the structural drawings corresponding to the Mechanical Room for the (a) 5th Floor and (b) 6th Floor.*

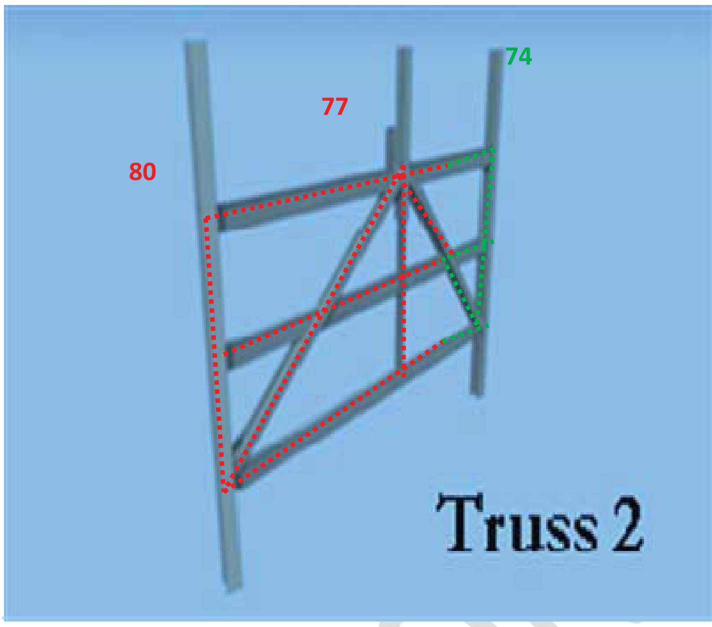


(a)

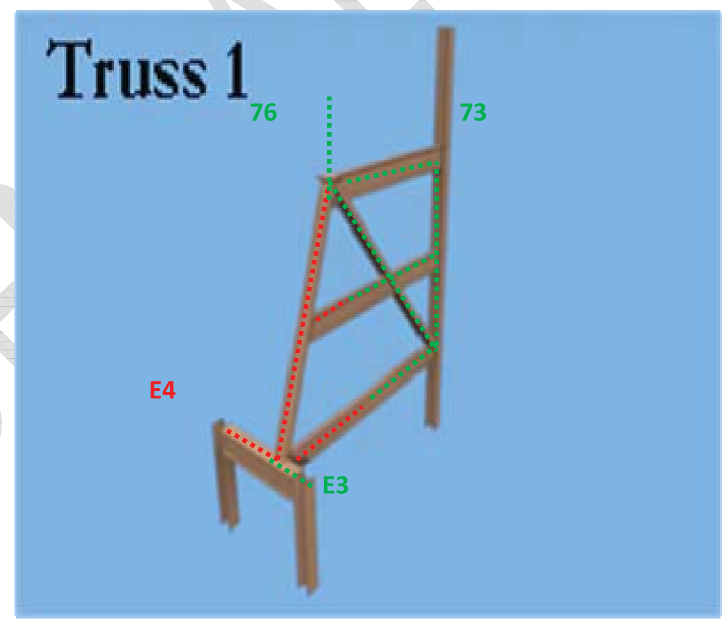


(b)

Figure 3 - *Schematic showing the location of Truss 1 and Truss 2. Figure 3(a) shows a three dimensional view of the structural elements without including the walls while Figure 3(b) shows a top view of the floor indicating the trusses in red, major columns in green, and the Mechanical Room in black.*



(a)



(b)

Figure 4 - *Schematic of Truss 2 (a) and Truss (1) showing in red the areas immersed within the Mechanical Room and in Green the areas outside the Mechanical room.*

2. Sequence of Events & Methodology

Examination of video footage of the collapse of WTC-7 has highlighted two distinctive events that characterised the collapse [7]. The first of these events was the fall of the East Penthouse into the building. The second was the appearance of a visual pattern running in the north-south direction to the east of the centre of the building. This pattern has been described by some as a "kink." The kink observed during the collapse is aligned with the mid-line of Truss 1 and west side of Trusses 2. The East Penthouse is principally supported by long span beams that run between Columns 79 and 80. Column 80 runs the entire height of the building and is supported at its base by Truss 2. These major structural elements and locations of the kink and penthouses are shown in Figure 5.

The coincidence of the location of Trusses 1 & 2 with both of the principal characteristics of the collapse sequence suggests that they played a crucial role in the collapse mechanism. This analysis will thus focus on the impact that a fire in the Mechanical Room had on the trusses and the resulting collapse of WTC-7.

The analysis was conducted by means of the following methodology:

- This analysis first characterized the potential fires within the mechanical room. using available experimental data, analytical expressions and a commonly accepted Computational Fluid Dynamics (CFD) tool developed by NIST called the Fire Dynamics Simulator (FDS). A range of potential fires was established and the thermal load imposed by the fires was applied to the structural elements.
- The thermal loading was applied in two stages, one without thermal insulation (fire proofing) and one with the as-built thermal insulation (7/8th of an inch per UL X772 requirements) to establish the delay induced by the fire proofing.
- The time evolution of the temperature for the structural elements was then calculated using a heat transfer analysis.
- The time evolution of the structural element temperatures was then introduced into a commercial structural Finite Element Model (FEM) called ABAQUS.
- A detailed analysis of the impact of loss of specific structural elements was conducted demonstrating that debris induced damage did not have an impact on the global structural behaviour. Thus, the models were built ignoring any structural damage associated to debris.
- Several models have been built to understand the behaviour of Truss 1 and Truss 2. The models include (a) a local model comprising the structural elements in the immediate vicinity of the trusses, (b) a two floor model that includes all structural elements in floors 5 and 6 and (c) a 15 floor model that includes all structural elements from floors 4 to 19.
- A series of studies using ABAQUS have been conducted to establish the behaviour of the structure when individual elements fail. Such systematic weakening of individual elements is referred to as "elimination analysis" throughout this report.
- Failure was induced by heating the structural elements until they entirely lost their strength. Heating rates were consistent with those imposed by a fire and

allowed a slow transfer of load from the failing structural element. This enabled identification of patterns that serve to validate conclusions and to discard certain potential scenarios as inapplicable.

- For all models global behaviour was emphasized, thus connection detail was omitted and all connections were assumed to be rigid, thus with unlimited strength. This assumption is valid throughout most of the heating period and only fails when the building is approaching failure. When steel members such as those in this structure are heated they expand and press against the structural members that restrain them. An expanded member is in compression which is not a critical condition for the connections. Throughout this period the heated structural element loses strength and loads get redistributed to other structural elements at a rate consistent with the heating rates. Thus no sudden load transfer is expected. Only when the steel member fails and starts to sag, unable to maintain the weight of the load it is supporting, does the connection become subjected to tension and in danger of failing. It is at this point that the assumption is no longer applicable. However, at this stage, all main characteristics of the building behaviour set forth in this report have already occurred and been identified. Thus it is deemed that this assumption does not affect the conclusions reached in this report. More details on this assumption are presented in Appendix1.

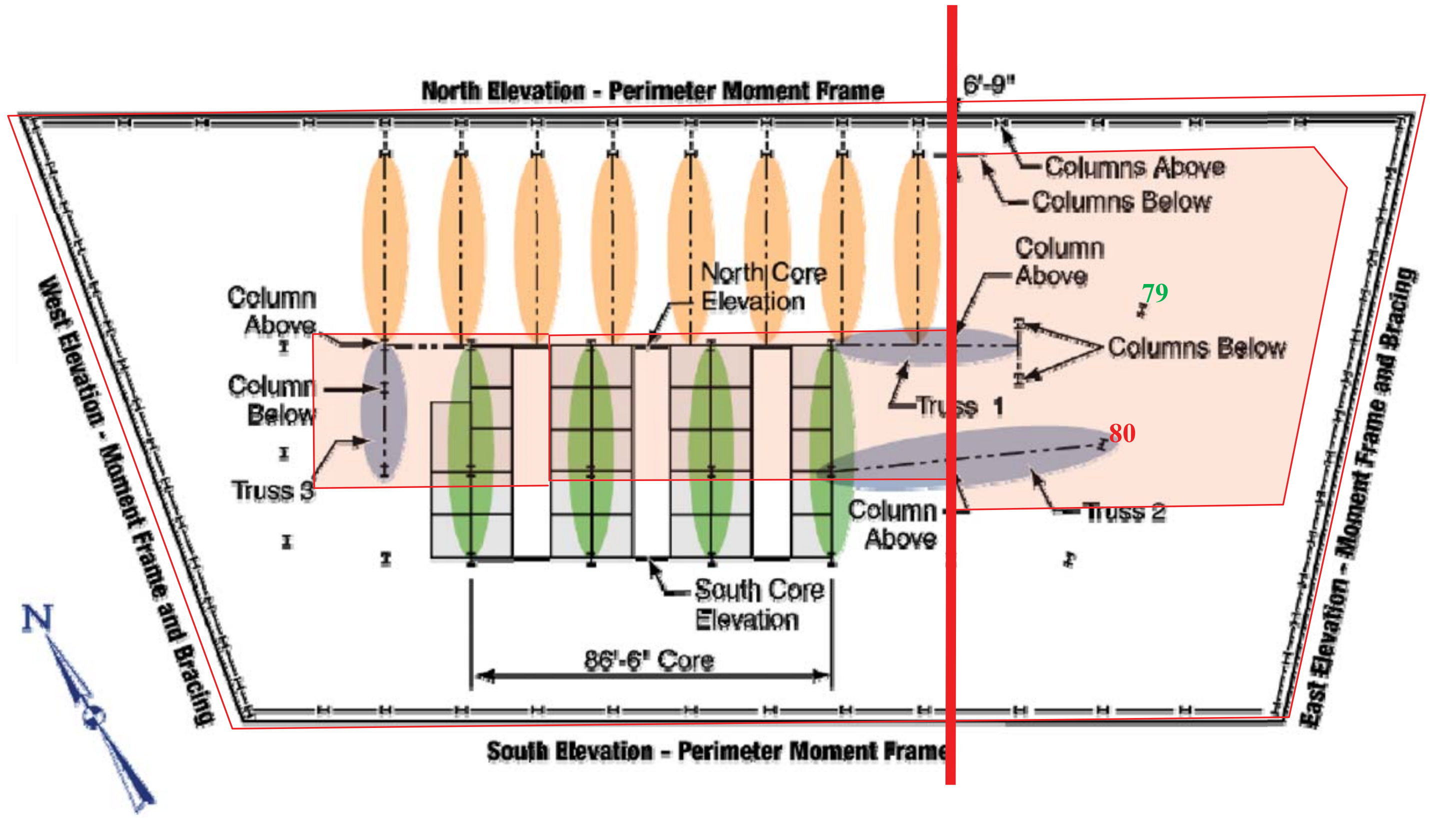


Figure 5 – *Outline of WTC7 with several important structural members shown in plan view. Superimposed is the location of the "kink" (red line) observed during collapse and that of the penthouses (thin red line with red shading), for comparison of horizontal location relative to each other. (Taken from [1])*

3. Potential Fires

The mechanical room was modelled in FDS. The main parameters controlling the temperatures of the compartment are the Heat Release Rate (HHR)[ii] and the heat losses through the compartment walls. The heat losses are a property of the material that was specified as concrete for all walls. The HRR is defined by Equation 1 if all the fuel produced is consumed.

$$HRR = A\ x\ HRRPUA^{ii}$$

Equation 1

The HRRPUA is the Heat Release Rate Per Unit Area[iii] and A is the burning fuel area. If there is not enough air to burn all the fuel, combustion is incomplete and the HRR is defined by Equation 2:

$$HRR = \dot{m}_{o_2}\ x\ \Delta H_{co_2}$$

Equation 2

where $\dot{m}_{O_2}$ $\dot{m}_{o_2}$ is the oxygen consumed by the combustion reaction and a strong function of the available ventilation and ΔH_{co_2} is the heat of combustion per kilogram of oxygen consumed, which is generally assumed as a constant value of 13.1 MJ/kgO_2. Given the HRRPUA, the burning fuel area (A), and the ventilation (openings or forced ventilation flow), FDS will calculate the distribution of temperatures within the compartment. Thus the three variables that need to be specified are ventilation, A and HRRPUA. Given that the exact values for each of these variables are unknown, the parameters were varied and the models then compared to establish the potential range of the fires. A total of 22 models were run varying the ventilation, HRRPUA and fuel area (A). The simulations were run until steady-state conditions were attained. The models showed the results were much less sensitivity to HRRPUA and burning area than to ventilation, so eight final ventilation conditions were conducted covering a wide range of air flows.

The mechanical room dimensions were approximated to 29.5m in length, 13.5m in breadth and 9.35m in height, in order to fit a regular grid [iv]. The background grid used to divide the compartment into cells of equal calculation properties is based on a 0.25m mesh in all plane directions, only locally refined to 0.125m round the truss columns. A sensitivity analysis of the grid cell size was conducted showing the appropriateness of the chosen configuration.

[ii] The Heat Release Rate refers to the amount of energy produced by the fire every second.

[iii] The Heat Release Rate per Unit Area refers to the amount of energy produced by the fire every second by each square metre of burning fuel.

[iv] Drawing S5 – Fifth Floor Framing Plan, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985), Drawing S5A – Fifth Floor Diaphragm Framing Plan, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985), Drawing S6 – Sixth Floor Framing Plan, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985)

Kerosene was used to model the fuel as it exhibits very similar properties to diesel and to remain within the parameters embedded in the model database. Its properties were taken from the FDS database and the defined HRRPUA was 750kW/m^2. Fuel has been supplied in the input file to ensure the fires burnt for long enough to produce steady-state conditions. It is the time it takes to reach steady-state that is relevant to these calculations. Steady state was attained in all cases between 300-600 seconds.

The models vented the room into the plenum and for model purposes the east-facing wall was open to the plenum, leaving only a 2.0 m hanger for smoke accumulation. The percentage of ventilation allowed was varied in the models by closing this face from the hanger down. One model also considered one of the back doors as open. The door dimensions were estimated as 2.5m x 2.5m and the results showed very little effect of this opening.

The geometry of the mechanical room was slightly adjusted to make it perfectly rectangular as the fire model requires a perfectly rectilinear grid. This would have a negligible effect on the modelled fires.

Only vertical truss members were modelled (again due to compliance issues with the models grid system) but this does not influence the information needed for analysis as temperatures for the diagonal members can be extrapolated and their inclusion in the model would have had negligible effect on the gas-phase temperatures generated.

Figure 6 shows the gas temperatures at each thermocouple location over time for Column 80. Thermocouples were placed adjacent to columns thus each column produced a different plot. The plots indicate that the gas temperatures rapidly reach a steady state value. Thus a constant gas temperature can be applied at each position for each column. Only one representative scenario is presented here, but similar data was obtained for all cases studied.

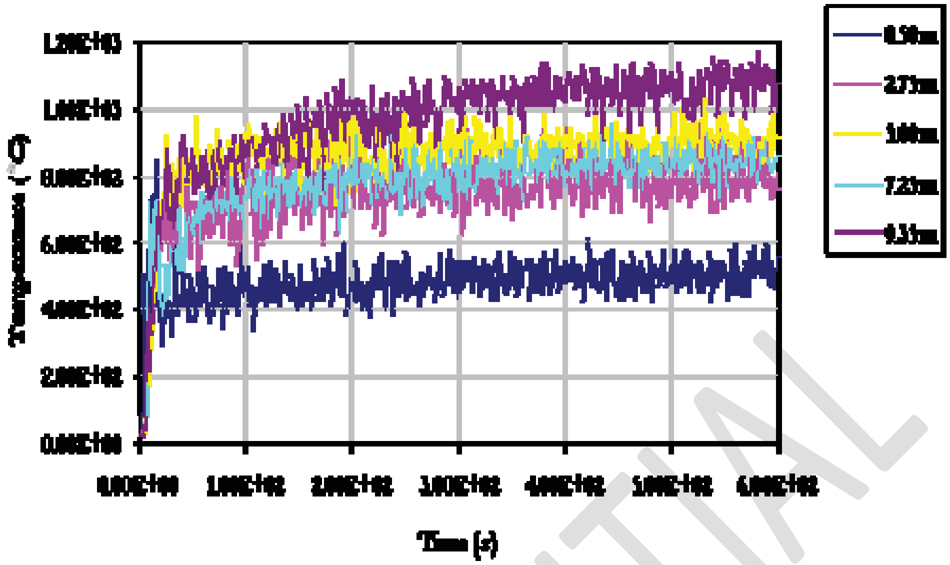


Figure 6 - *Evolution in time of gas temperatures at various heights adjacent to Column 80. The height is measured from the floor of the room and indicated in the legend. Steady state was achieved after 400 seconds.*

The temperatures fluctuate considerably, mostly due to the calculation methods embedded in the FDS program, however a general trend was obvious and the time for each column gas-phase temperatures to reach steady-state was identified. The values were then averaged to show a representative value of temperatures over this steady-state period. Figure 7 shows the temperature variation adjacent to Column 80 for steady-state conditions (irrespective of time). Similar plots were obtained for all other immersed columns.

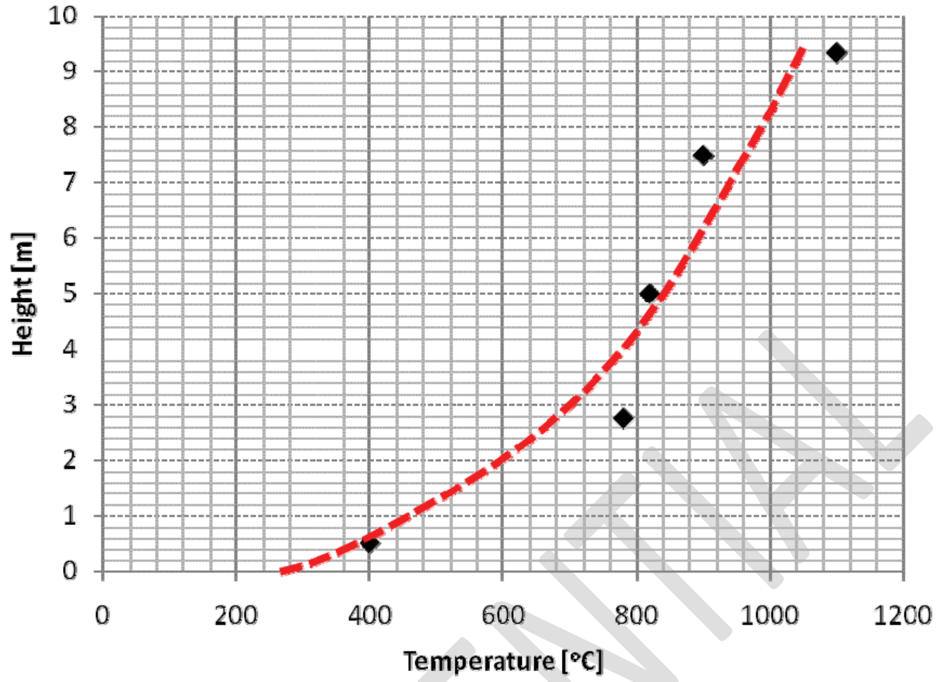


Figure 7 - *An example plot of the thermocouple (gas-phase) temperature variation with height for Column 80 under steady-state conditions.*

For verification of the FDS modelling the FDS temperature results were averaged and compared to the classic experimental temperature distributions produced by Thomas and Heselden [2]. Thomas and Heselden define an average compartment temperature as a function of an "opening factor." The opening factor is dependent on the ventilation parameters of a compartment and Thomas' experimental data correlated this factor to average temperatures achieved in a post-flashover fire. In this case, comparison is made with Thomas curves, as opposed to Pettersson et al [3] or Magnusson [4] and Thelandersson [5] curves for example, because the latter models represent post-flashover fires that become fuel-limited and decay without reaching steady-state burning conditions. So the fires in Thomas' experiment were most similar to the prolonged post-flashover fires thought to have occurred in WTC 7. The opening factor for each compartment was defined as:

$$Opening\ Factor = \frac{A_T}{(A_v \times \sqrt{H_v})}$$

Equation 3

where A_T is the total internal surface area of the compartment excluding the opening, A_v is the area of the opening and H_v is the opening height.

For comparison, the opening factors of each of the models in the mechanical room were calculated and the average room temperature estimated and presented in Figure 8. The results generally under-predict Thomas' data which is expected given the geometry of the compartment. Thus, even the most severe temperatures calculated by the model are likely to be lower than reality. Thus for the purpose of the heat transfer calculations the fire model results leading to the highest temperature were used. Compared to Thomas' experimental data this would have still remained as a conservative temperature estimation.

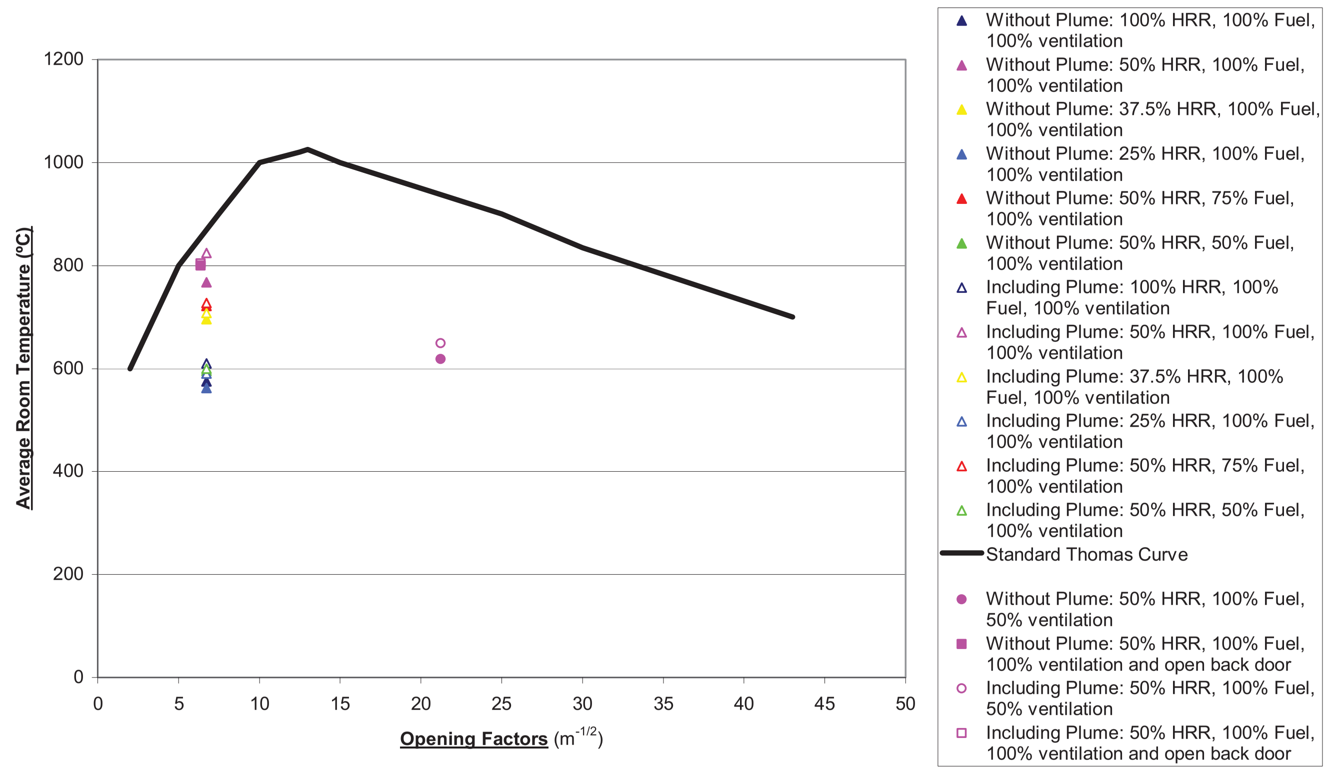


Figure 8 - *Mechanical Room average temperatures and opening factors compared to the standard Thomas Curve for post-flashover fires in steady-state conditions. The % of the HRR indicates percentage of Kerosene, the % Fuel indicates percentage of floor area covered by fuel, % ventilation includes percentage of East wall open and With/Without Plume correspond to computational domain that includes venting to the outside and restricted venting respectively.*

4. Heat Transfer Calculations

For the Mechanical Room Fires a large temperature gradient between the top and the bottom room was evident (Figure 7). This is mainly due to temperature increase at the top caused by a hot smoke layer. This gas-phase temperature gradient will have a significant effect on the distribution of the column temperatures. To determine the column solid-phase temperatures a Fin Heat Transfer model was used. For this particular case the following energy conservation equation was used.

$$-kA\frac{\partial^2 T}{\partial x^2} + hP(T_0 - T) = 0$$

Equation 4

Where, k is the thermal conductivity, A the cross sectional area of the structural element, h a total heat transfer coefficient, P the exposed perimeter of the structural element, T_0 the gas phase temperature and T the average temperature of the structural element. The properties used were

Steel thermal conductivity, k = 14.5W/mK
Steel convective heat transfer coefficient, h = 45 W/m^{2}K

The dimensions were directly obtained from the design drawings for each individual structural element.

It was found that the resultant column temperatures were constantly within one or two degrees of the gas-phase temperatures, under steady-state conditions, a difference which is negligible relative to the overall temperatures. This shows that for these columns conduction does not affect the temperature distribution. Most likely only very localised conductive heat transfer occurs, if any at all. The column geometry and dimensions render its surface area very large comparative to its cross-sectional area ($P >> A$), so heat transfer is more prominent in the form of convective and radiative heat exchange between the column and the gas-phase surroundings. Hence it can be assumed that at steady-state the column solid-phase temperatures are the same as the gas-phase temperatures.

During the fire growth period, heat produced is also affecting the column temperatures. Even though the column temperatures under steady-state conditions are similar to those of the fire gas-phase temperatures surrounding it, the column has a delayed response and takes longer to reach steady-state temperature. To find out the time lag of the column temperatures in reaching steady-state, the column temperatures were modelled, ignoring conduction and re-radiation effects. The average fire temperature applied was approximated from the mid-height thermocouple temperature-time variation from the worst-case scenario thermocouple output. The column temperatures were modelled using the following energy balance for increments of column with equal cross-sectional area:

$$A\rho C_p \frac{\partial T_s}{\partial t}\partial x = hP\,(T_g - T_s)\,\partial x$$

Equation 5

where T_g is the gas-phase temperature and T_s is the steel column solid-phase temperature.

The initial temperature of the steel column is assumed to be at ambient temperature, such that $T_{s,0}$ = 20ºC (293K) for t = 0sec. Again, the same column properties were used as for the Fin model, together with the following data:

Steel thermal capacity at constant pressure, C_p = 475J/kgK
Steel density, ρ = 7850kg/m^3

To simplify the modelling of each of the columns' temperature-time response, a linear approximation of the temperature growth period was taken. The variation of the column temperatures under steady-state had already been modelled as functions of $f(x^2)$, so to allow for application of the column temperature regression equation over the whole height of the columns, the following linear regression was taken for the column temperature transition periods:

$$T_T = \left(\frac{(f(x^2) - T_{amb})}{t_{g,90\%}}\;t\right) + T_{amb}$$

Equation 6

where $f(x^2)$ was taken as the separate functions defining the temperature variation of each column, the ambient temperature, T_{amb} was taken as 20ºC (293K) for initial conditions before the fire, $t_{g,90\%}$ is the time for the columns to reach the assumed steady-state temperatures, and t is the variable time over which the temperature is transient in each column.

The temperatures of each column as a function of column height (x) from the floor upwards and as a function of time (t), can be summarised as follows, where T_T is transient temperature and T_C is constant temperature over time, but varying with height:

COLUMN E4

$$\begin{cases} T_T = ((3.5\mathbf{x}^2 - 26.6\mathbf{x} + 708.3) / 9270) * \mathbf{t} + 293 & \text{for } 0 < \mathbf{t} < 9270 \text{ sec} \\ T_C = 3.5\mathbf{x}^2 - 26.6\mathbf{x} + 1001.3 & \text{for } \mathbf{t} > 9270 \text{ sec} \end{cases}$$

COLUMN 77

$$\begin{cases} T_T = ((-4.2\mathbf{x}^2 + 93.2\mathbf{x} + 481.8) / 9510) * \mathbf{t} + 293 & \text{for } 0 < \mathbf{t} < 9510 \text{ sec} \\ T_C = -4.2\mathbf{x}^2 + 93.2\mathbf{x} + 774.8 & \text{for } \mathbf{t} > 9510 \text{ sec} \end{cases}$$

COLUMN 80

$$\begin{cases} T_T = ((-2.7\mathbf{x}^2 + 15.8\mathbf{x} + 1029.3) / 9770) * \mathbf{t} + 293 & \text{for } 0 < \mathbf{t} < 9770 \text{ sec} \\ T_C = -2.7\mathbf{x}^2 + 15.8\mathbf{x} + 1322.3 & \text{for } \mathbf{t} > 9770 \text{ sec} \end{cases}$$

The variation in the temperature distribution between the three columns is small enough that it can be considered appropriate to average out these distributions and produce only one set of temperature-time equations to represent the whole room. In any case, a standard deviation error bar has been added to the transient temperature equation to allow for slight variations. This represents the compartment as linearly stratified, at least in the local area around the columns. This means the temperature of the truss members spanning between these columns are also governed by the same general equation derived, with the distance along the member **x** referenced vertically from the floor in perpendicular height.

The temperatures down each column were averaged and again producing a $f(x^2)$ best-fit line for the distribution, a transient regression was recalculated. The general temperature-governing equation for the structural members in the mechanical room is:

GENERAL COLUMN TEMPERATURE

$$\begin{cases} T_T = ((-1.1\mathbf{x}^2 + 27.5\mathbf{x} + 739.8) / 9583) * \mathbf{t} + 293 \pm 200 & \text{for } 0 < \mathbf{t} < 9583 \text{ sec} \\ T_C = -1.1\mathbf{x}^2 + 27.5\mathbf{x} + 1032.8 & \text{for } \mathbf{t} > 9583 \text{ sec} \end{cases}$$

Temperature-time curves were plotted for the top, middle and bottom of the columns to show the variation of temperature across column height. A standard temperature-time curve of $T = T_o + 345 \log(0.133t + 1)$ according to ASTM E119. Although the standard design curve represents gas-phase temperatures as opposed to the column solid-phase temperatures, it is still useful for comparison as the column temperatures attain the gas-phase under steady-state conditions. So towards the later stages of the heating, the values can be compared.

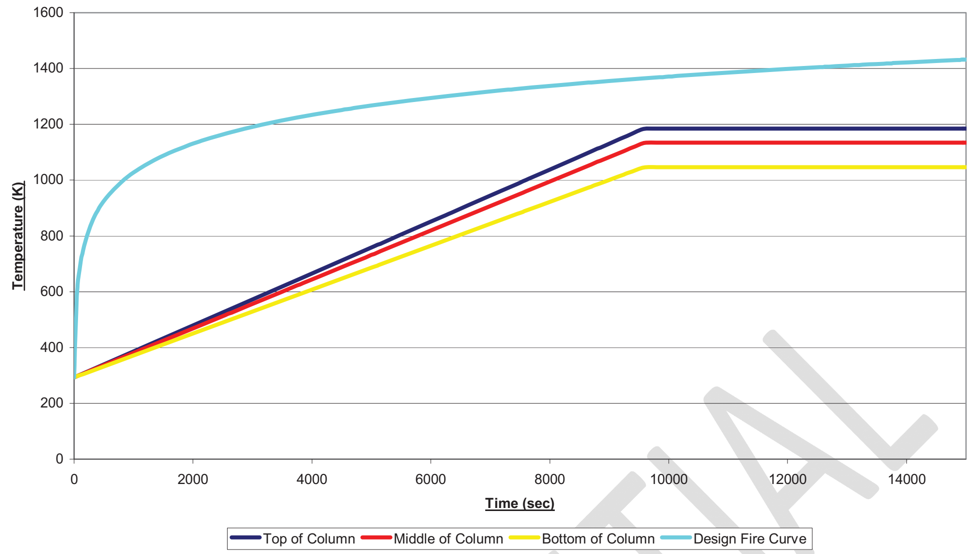


Figure 9 - *Graph of the temperature-time variation of the columns in the mechanical room under modelling results corresponding to the worst-case scenario fire, with a standard design fire curve for reference.*

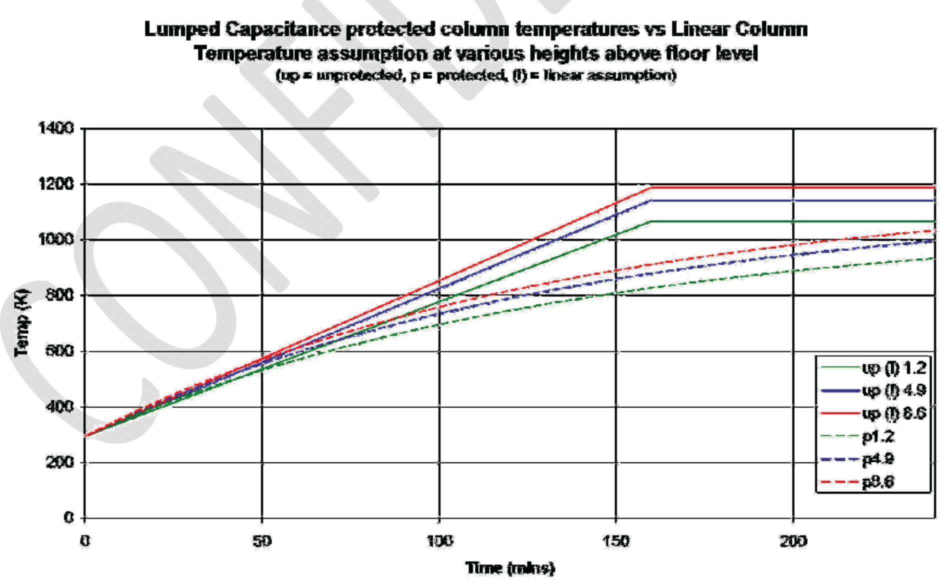


Figure 10 - *Temperature evolution for the bare (up) and insulated (p) structural elements as a function of height. The three values correspond to three typical heights 1.2 m, 4.9 and 8.6 m.*

The simplifications presented in this section are necessary because of the nature of the Finite Element Model that requires the definition of the temperature at each node for each time step. Simple functions like the ones presented above allow introducing this data in an efficient manner without changing the methodology, reliability, or the ultimate outcome of the analysis.

Fire proofing tends to have only a minor effect on the temperature rise for very large structural elements like the truss components under discussion here. Thus the effect of thermal insulation was introduced on the basis of a simple lumped capacitance analysis as indicated in the SFPE handbook for Fire Protection Engineering [6]. The results are shown in Figure 10 and indicate a time delay no greater than 20% when the temperature is below 800K. Larger errors can be attained for higher temperatures but given the characteristics of failure it was not necessary to refine this calculation and failure times will be estimated using the non-insulated scenario assuming a potential error of 20% associated to the insulation.

A common rule of thumb is that structural steel will typically lose a significant proportion of its load bearing capacity by the point at which it reaches 550 - 600˚C (823 – 873K). Nevertheless, the loss of strength occurs in a progressive manner as the structure heats up. Thus loads redistribute continuously during the heating process. Upon reaching 550 - 600˚C (823 – 873K) you would expect the member(s) affected to have lost most of their strength and to be unable to continue to support the loads they did previously, and for the load to be almost fully redistributed by the structure to other members. This additional loading in the affected members would most likely result in them becoming overloaded and yielding, again implying a further load redistribution. If this sequence continues, the number of remaining supporting members continues to decrease and eventually a global collapse will occur. It is a sequence such as this that the elimination analysis described in the following section demonstrates. Thus through the application of the thermal loading described in Figure 10 in turn to each of the structural elements of interest, it was possible to establish which of them were most critical to the global structural stability, to which other structural elements loads redistributed upon their loss of strength or failure and what visible deformations resulted from the loss of strength of a specific structural element. By comparison with the videos and photographs it was possible to establish the most likely collapse scenario by discarding those which did not match the visual evidence of the collapse of WTC-7.

5. Elimination Analysis and Scenario Matching

A complex building collapse scenario like the one addressed here includes a large number of potential failure events. Thus, it is more relevant to address the reconstruction of the events via an elimination analysis than to try to establish the exact sequence of events. The elimination analysis tests a series of hypotheses and eliminates the ones which could not lead to the observed sequence of events. Those remaining are then tested to establish if the different observations could be reproduced given that scenario analyzed. While much more laborious, this process is more robust than a single reconstruction of the events because it analyzes and discards all other potential options that do not match the observed scenario. Furthermore, it identifies not one sequence of events but all plausible sequences.

Through the elimination analysis a series of different scenarios were concluded to not produce the observed sequence or the nature of events. Failure of several structural elements was analyzed showing that deformations and sequencing were not consistent with what could be observed through diverse images and video footage[i]. The scenarios eliminated will not be discussed here and instead focus will be given to those leading to events that could be correlated with the evidence.

The main scenarios that resulted in behaviour that could be directly associated to the visual evidence are mainly linked to the failure of Truss 1 (Columns E3, E4, 73, 76), Truss 2 (Columns 74, 77 and 80) and Column 79. The following sections will provide a summary that explains the most plausible sequence of events.

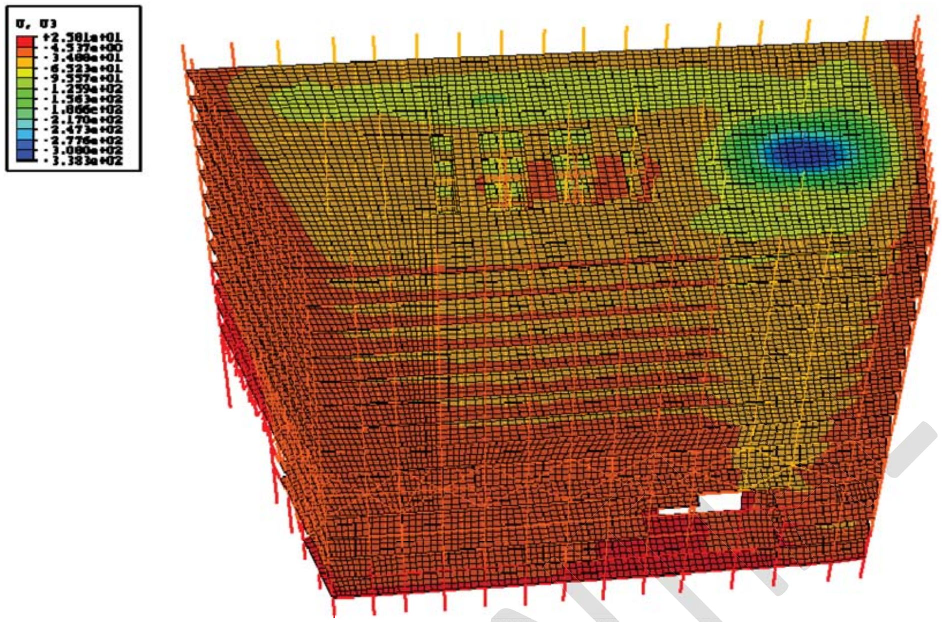
In the event of a fire in the mechanical room, Columns 77, 80 and the elements that link them have the largest potential exposure to heat. The effect of the failure of these elements is discussed in-depth below.

5.1. Elimination of Columns 77 and 80 (East (exposed) part of Truss 2)

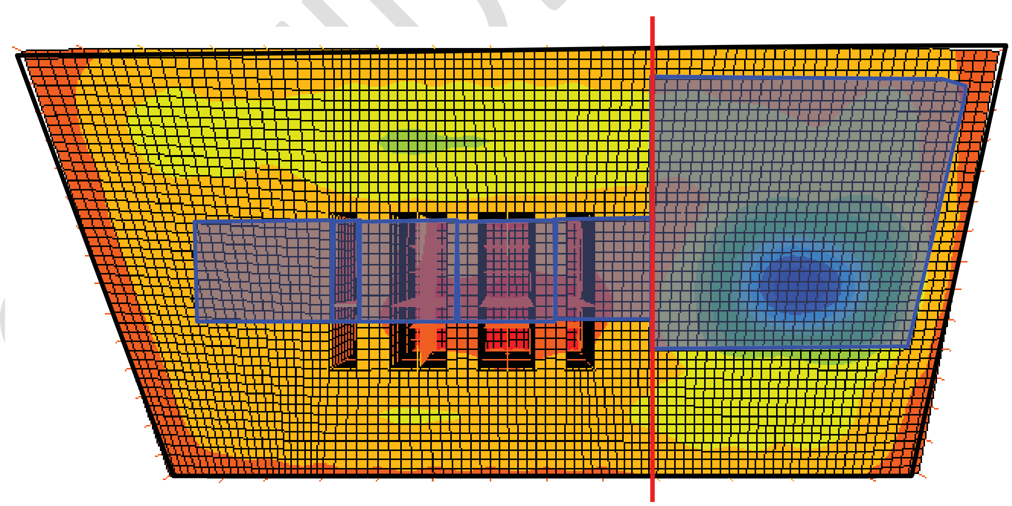
The strength of each individual element was reduced by increasing its temperature to establish the nature of the deformations and the load redistribution paths. The section of Truss 2 heated was defined according to the explanation provided in Section 1 and Figure 4. When Columns 77 and 80 were heated, it was observed that the largest region of vertical descent was below the symmetry plane of the penthouse. This can be seen in Figure 11, where the blue region shows the area of maximum vertical descent.

In a similar manner, the reduction of strength of Column 79 resulted in vertical deformations aligned with the symmetry plane but placed north of the deformations observed when heating Columns 77 and 80. Figure 12 shows in blue the area of maximum vertical descent.

[i] Expert Report by Frederick W. Mowrer, Ph.D., Exhibit B: GNA Photographic Analysis Report

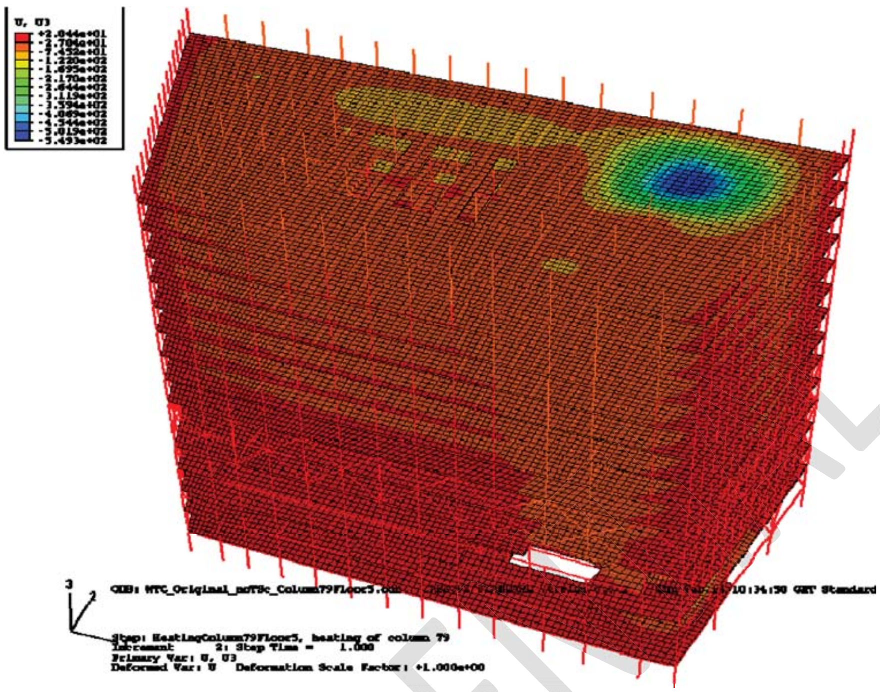


(a)

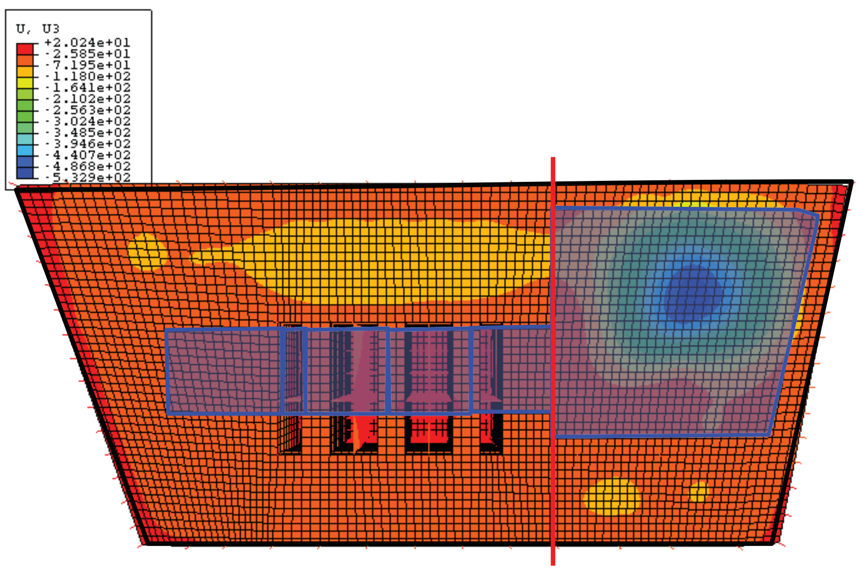


(b)

Figure 11 - *Deformations generated by the reduction of strength of Columns 77 and 80.*



(a)



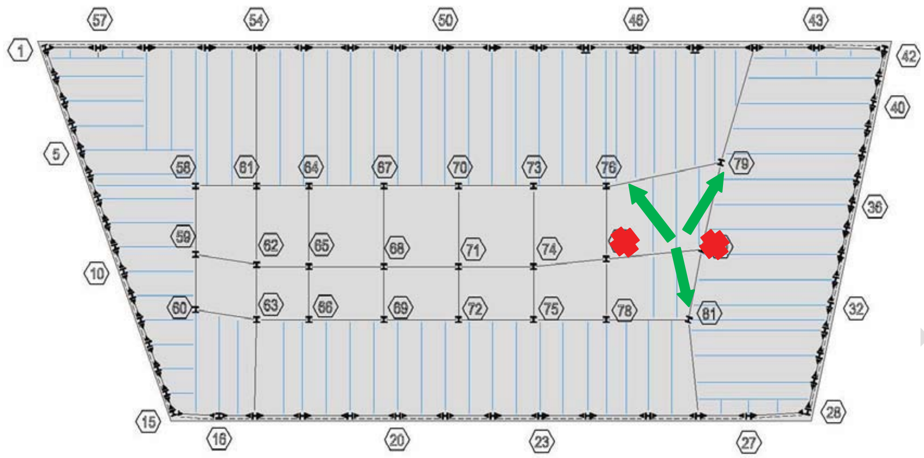
(b)

Figure 12 - *Deformations generated by the reduction of strength of Columns 79.*

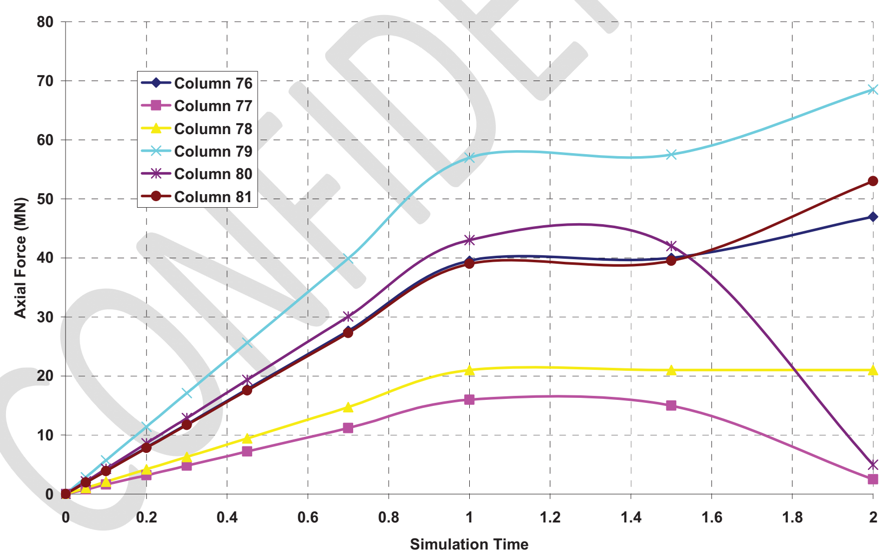
The above images confirm that weakening of either Column 79 or of Columns 77 and 80 result in deformations that are consistent with the observed first event preceding the collapse of WTC-7. The deflection patterns coincide with the footprint of the East Penthouse but not with the line of the kink. A fire in the mechanical room would lead to the loss of strength of the most exposed structural elements and the deformations observed would manifest themselves with the sinking of the East penthouse.

The model allows for the examination of the redistribution of force within the framing system to demonstrate the effect that a loss of strength would have on other elements of the framing system. This enables a better understanding of how the loads originating from the weakening of a structural element are transferred towards other structural elements.

Figure 13(b) below shows the axial forces induced in different columns when Columns 77 and 80 lose strength. The time indicated is an artificial time corresponding to the numerical loading of the structure. From 0 to 1 the dead loads of the structure are applied and compressive load is seen to increase as this happens. At time=1, Columns 77 and 80 start heating up and thus losing their strength. By time = 2, Columns 77 and 80 have no strength left, thus the axial load that they are carrying is almost zero (Figure 13(b)). As indicated in Figure 13(a) the loads redistribute mainly towards Columns 76, 79 and 81. This is evidenced by a further increase in the axial load of these three structural elements (Figure 13(b)), with Column 79 being the highest loaded column. From the resulting load distribution following the loss of strength of Columns 77 and 80, there is in an increase in the axial load carried by Column 79 showing that the redistribution of load would place Column 79 at the limit of its load bearing capacity even before any weakening due to heating from other fires. It is important to reiterate that, as shown in Figure 13(b), load transfer occurs progressively as the temperature of the affected structural element increases and its strength decreases.

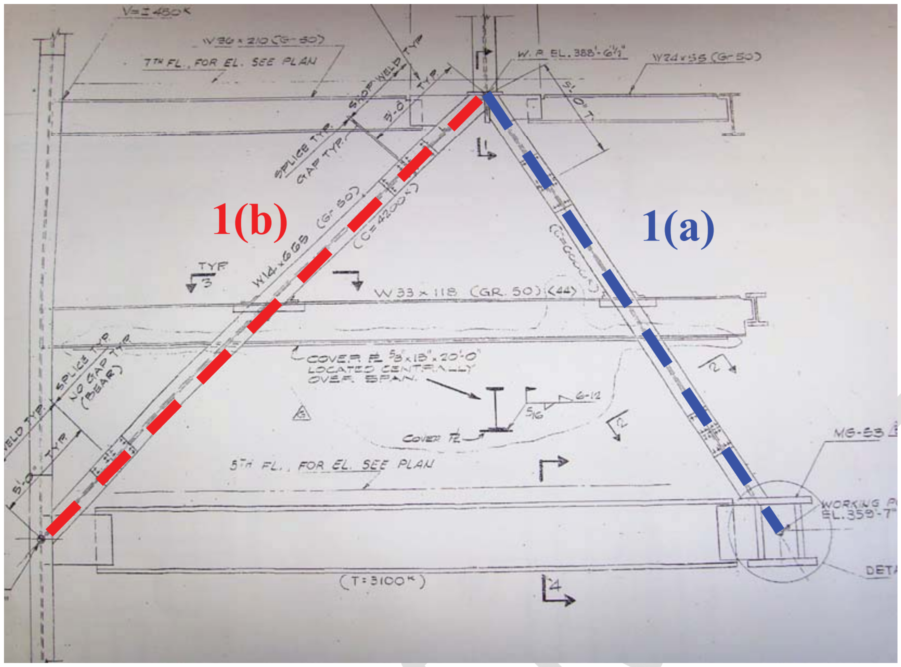


(a)

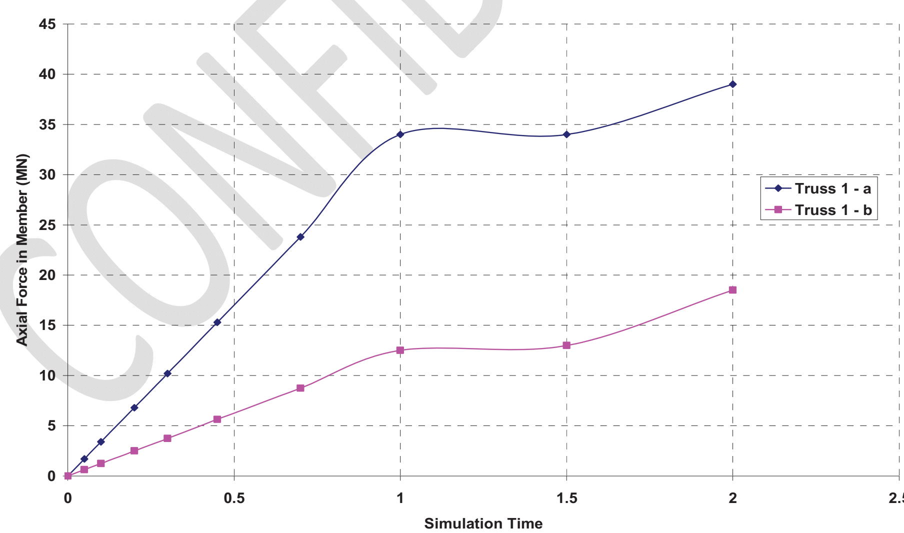


(b)

Figure 13 - *The plot shows the resultant change in axial force in the six internal columns to the east of the core following the reduction of strength of Columns 77 and 80 to the point of complete loss of structural integrity.*



(a)



(b)

Figure 14 – *The plot shows the increase in axial force in the two diagonal members of Truss 1.*

Blueprints	*ABAQUS*	
Expected Design FoS	**Model Output FoS**	**TRUSS**
100%	99%	1b
100%	68%	1a

Table 1 – *The table shows changes in Factor of Safety ("FoS") associated to the diagonal members of Truss 1 based on the increases in axial forces shown above in Figure 14. The Design FoS is presented as a percentage of the expected forces in the members (outlined in the structural blueprints) when compared to the member capacity. The model output FoS is presented as a percentage of the Design FoS and is based on the forces produced in the members following heating.*

Figure 14(b) shows the increase in axial force experienced by the diagonal members of Truss 1 as the load is redistributed following the "heating" of Columns 77 and 80. This has the effect of lowering the FoS of the members. The FoS of the eastern-most diagonal member (1(a)) is lowered to approximately 68% of its design value (Table 1) indicating that this member is approaching its limit of capacity. It is important to note that in this analysis Truss 1 remains at ambient temperature. An increase in temperature will clearly further reduce the FoS. This will be discussed in the following section.

The overall pattern that has been demonstrated is that a significant part of the load has been redistributed north along the line of the kink and north east towards Column 79 pushing the structural members in these regions toward the limits of their respective load bearing capacities. The analysis of a Truss 2 failure above indicates that there would be a significantly increased loading on Truss 1. It also shows that Column 79 would be loaded potentially right to the limit of its capacity.

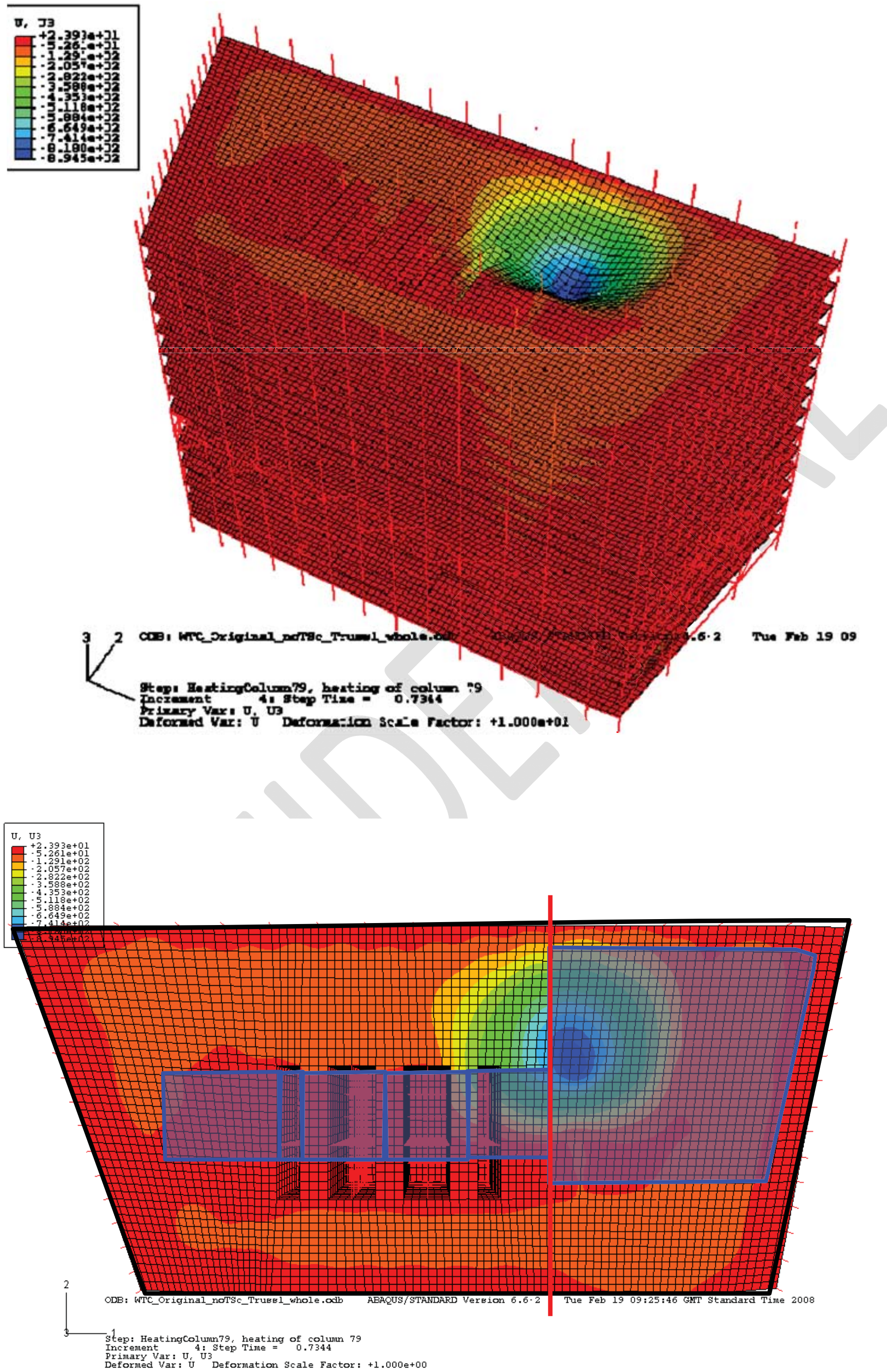


Figure 15 – *The image shows the deflection patterns resulting from the failure of Truss 1 due to imposed thermal loading. The epicentre of the deflection pattern is centred on the kink location and significantly, also extends to the core of the building.*

5.2. Elimination of Truss 1

For completeness in the elimination study, and in order to ascertain its structural importance, the same methodology was applied to Truss 1. While section 1 indicates that heating of Truss 1 would have not been as severe as heating of the East section of Truss 2 (Section 5.2), it is still of importance to establish the impact of reducing the strength of Truss 1. This analysis is not intended to define failure of Truss 1 as an initiating event but to enable the understanding of what visual evidence is associated to the failure of this Truss.

The weakening of Truss 1 due to thermal loading will result in vertical displacements as indicated in Figure 15. As would be expected, the epicentre of the displacement pattern lies directly over the kink (Figure 5). At the time the simulation finished, results indicated that loads were being redistributed to the core, to Columns 74, 77 and 80 (above Truss 2) and Column 79.

It is important to note that as Truss 1 weakened, load paths changed higher in the structure, redirecting load inward towards the core and Truss 2, and showing little to no load transfer towards the external structural elements. This suggests that load redistribution from Truss 1 will result in large global displacement of the core before there is any visible external evidence of what is happening with the structure.

The deformation and load redistribution patterns associated to the weakening of Truss 1 indicate that the failure of Truss 1 would have severe implications for the structure. The deformations appear consistent with the formation of the kink and the final collapse sequence, nevertheless they do not show evidence consistent with the sinking of the East penthouse. Thus, failure of Truss 1 plays a significant role in the collapse of WTC-7 but cannot be the initiating event.

5.3. Combined Elimination of Truss 1 and Truss 2

An analysis of the effects of the failures of Trusses 1 and 2 was carried out. The displacement pattern produced followed even more closely that of the observed kink (Figure 16). Once again the failure progressed to the core indicating that this would have compromised the overall stability of the structure in a manner consistent with the kink and subsequent collapse. Thus combined failure of both Trusses will result in the final event observed in video footage and photographs.

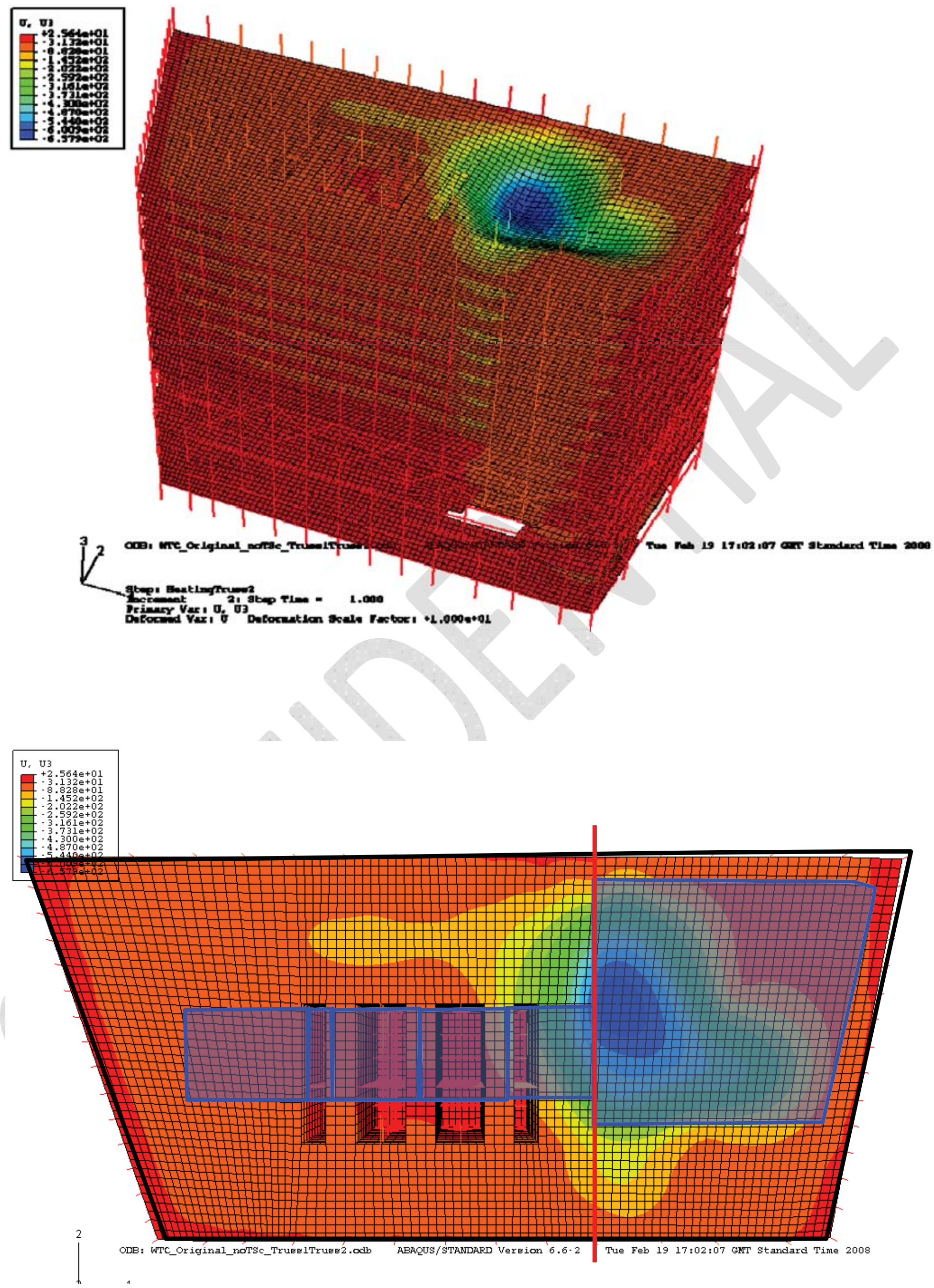


Figure 16 – *Vertical displacement patterns caused by the heating to failure of Trusses 1 and 2. These patterns correspond almost exactly to the location of the kink and coincide strongly with the east end of the building's core.*

5.4. Diesel Fuel Fire in the Vicinity of Column 79

The elimination analysis and Mechanical Room fire scenarios did not address the possibility of the collapse sequence being initiated by a diesel fuel fire within the North-East quadrant of WTC-7, outside the Mechanical Room. This section provides an assessment of the effect that a diesel fuel fire in the north-east quadrant of the 5th floor, in the vicinity of Column 79 would have on the global collapse WTC-7.

A preliminary CFD analysis of the area surrounding Column 79 on the 5th-6th floors was conducted to determine the possible exposure of this column to diesel fuel fire and enable a structural analysis to be conducted to determine the degree of potential damage to this column and resultant effect on the global structural behaviour. Given the quantities of diesel fuel known to be stored in this area, the large dimensions of the compartment, and the complexity of the air supply due to the fan and plenum systems in place there, it was deemed necessary to perform a detailed analysis of this space in order to assess the possible range of fire severity. A model was constructed using FDS with a grid size of 0.25m x 0.25m x 0.25m. External boundaries of the domain and the south west opening to rest of the 5th floor were described by free, open boundaries. The compartment was 4m high. A plan view of the model is depicted in Figure 17.

Analysis of the output of these models allows the definition of the temperature fields given the variety of possible ventilation conditions. A virtual thermocouple tree was defined close to the north facing side of Column 79 in order to assess the evolution of the gas phase temperature. The results of the first aspect of the sensitivity study showed that the opening or closing of internal doors, fan cavities, and external windows had very little effect on the internal temperature range with respect to the temperature exposure of Column 79. A scenario of closing the doors to the north-west rooms, but leaving the windows, plenums and, in the case of 0 m/s fans, fan cavities all open was finally adopted. A fan speed sensitivity study was then conducted to establish the effect on the compartment temperatures and in particular on the gas phase around Column 79.

The results indicated that the most severe temperature exposure of Column 79 is the scenario of natural convection, i.e. no forced ventilation from the fans. A linear approximation of the results of this worst condition scenario is presented in Figure 18. The linear approximation was conducted using the same methodology presented in Section 3. The conclusion of these CFD simulations is that the potential heat insult on Colum 79 is comparable to the heat insult calculated in Section 4 for the Mechanical Room. Therefore, the analysis of the behaviour of Column 79 was done using the same temperature evolution described in Section 4.

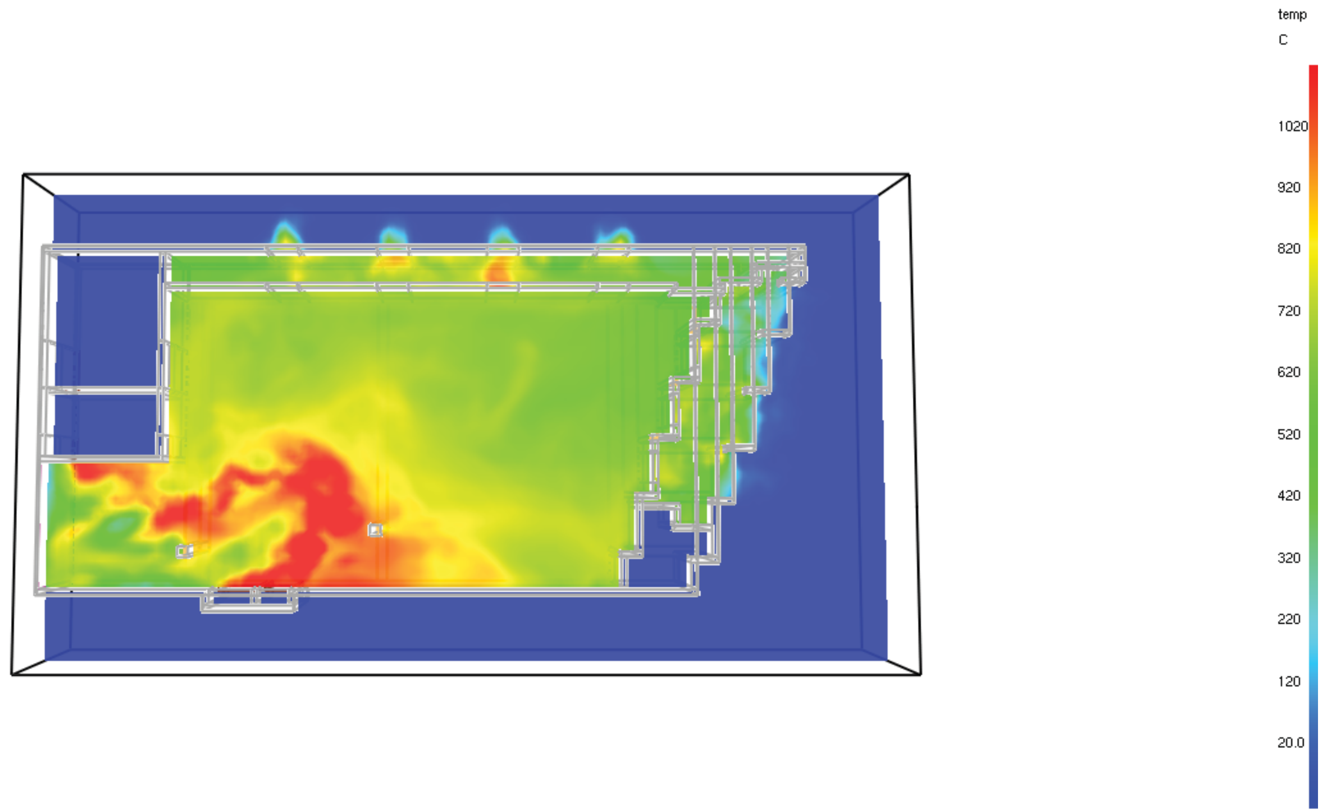


Figure 17 - *A slice file taken from FDS model corresponding to the highest temperatures.*

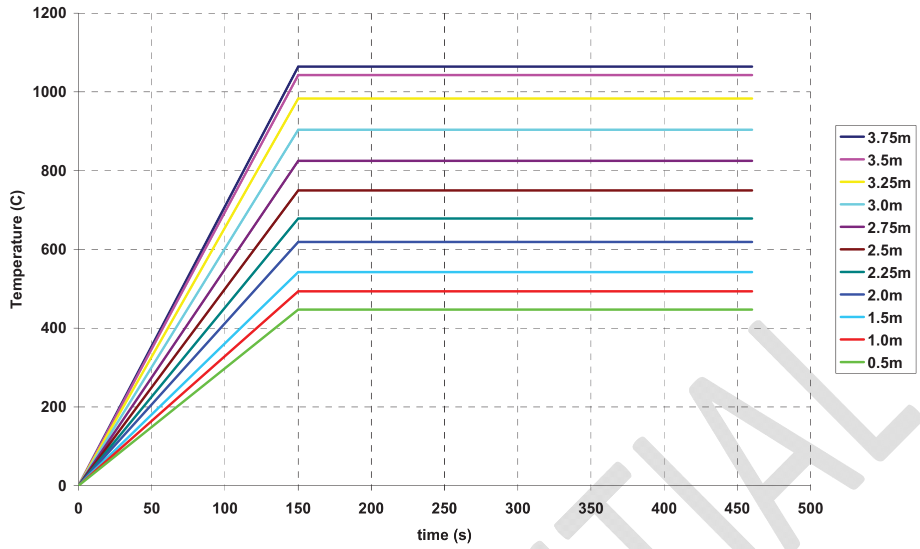


Figure 18 – *Linear approximation of the evolution of gas phase temperatures in time at different heights around Column 79 at the 5th to 6th floor level.*

The 15 storey Finite Element Model (FEM) was run showing the force redistribution that would result from a loss of load bearing capacity due to heating of Column 79. Trusses 1 and 2 were left fully intact for these models to isolate the contribution of this column. The model heated Column 79 between floors 5 and 6. The largest deflections were centred, as would be expected, on the location of Column 79 beneath the East Penthouse (Figure 19). This indicates that failure of Colum 79 due to a fire in the north-east quadrant of the 5th floor provides an initial event (sinking of the penthouse) that is consistent with evidence.

Weakening of Column 79 systematically transfers load through the heating period. Figure 20 indicates that the redistributed load is carried mainly by Columns 76 (above Truss 1) and 80 (Truss 2). The resulting increase in axial loading carried in the diagonal members of Truss 1 is shown in Figure 21. Figure 21 indicates that these diagonal members significantly increased their load as Column 79 weakened due to heat. A similar effect can be seen on the east diagonal of Truss 2. The analysis also shows that the nearby northern façade columns also carried an increased loading.

In summary, this section of the analysis demonstrates that the loss of structural load bearing capacity in Column 79 at this level of the building would lead to an increased loading of Trusses 1 and 2 (eastern columns and diagonals) following redistribution. The deflection pattern suggests that the onset of failure would have been the fall of the East Penthouse, and that load transfer would induce failure of Trusses 1 and 2, leading to the generation of the "kink." This load redistribution onto Trusses 1 and 2, combined with the likely loss of strength due to diesel fuel fires around Column 79 will most likely lead to the failure of Trusses 1 and 2 and the global collapse in a manner similar to that described in the previous sections. The deformations associated to this mode of failure are also consistent with the visual evidence of the collapse of WTC-7.

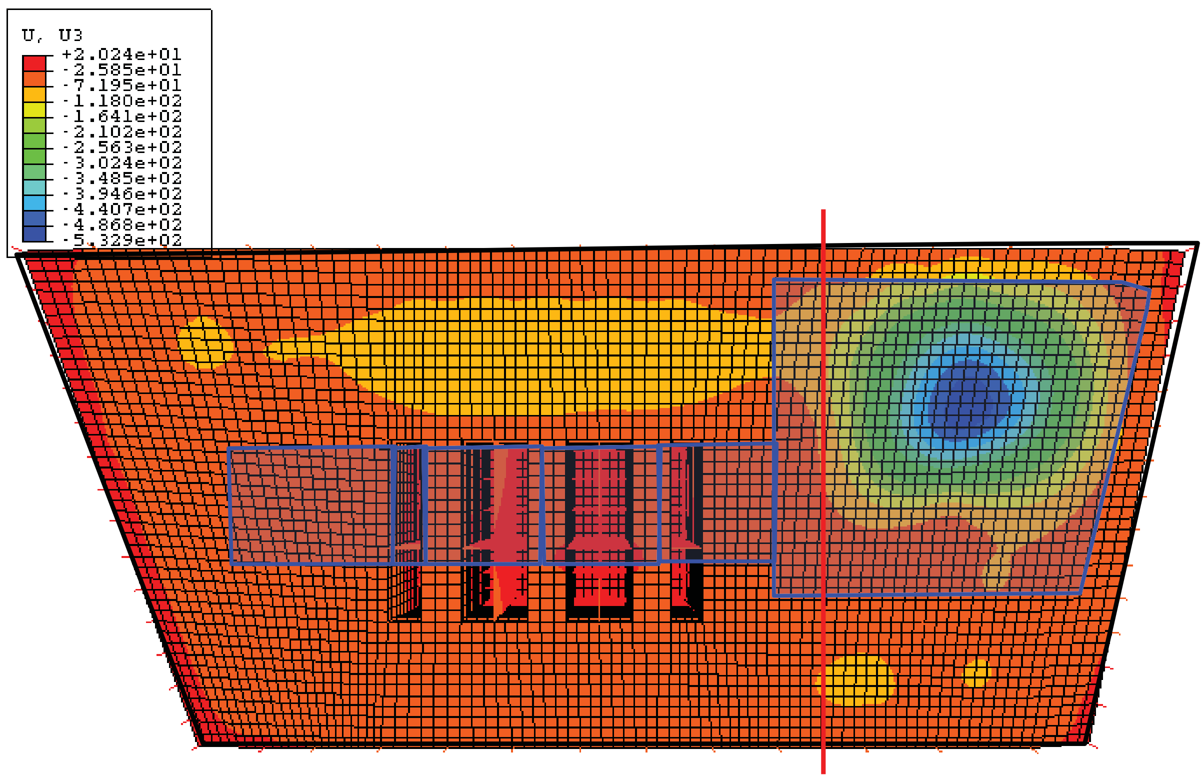


Figure 19 – *The image shows the deflection pattern following the heating to loss of structural integrity of Column 79 between the 5th and 6th floors. A similar pattern is seen for heating of the same column between the 12th and 13th floor.*

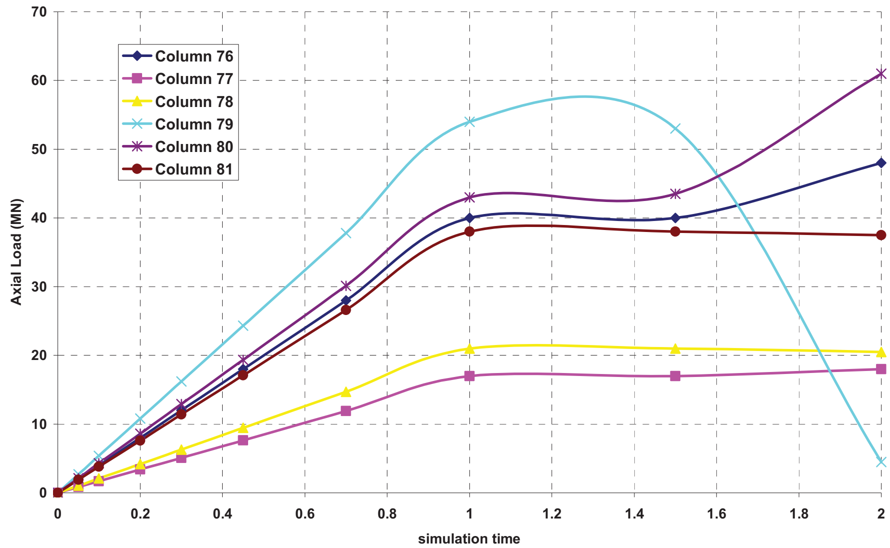


Figure 20 – *The plot shows the increase in axial force in the internal columns to the east of the core following the redistribution of forces resulting from the imposed heated failure of Column 79 between floors 5 and 6.*

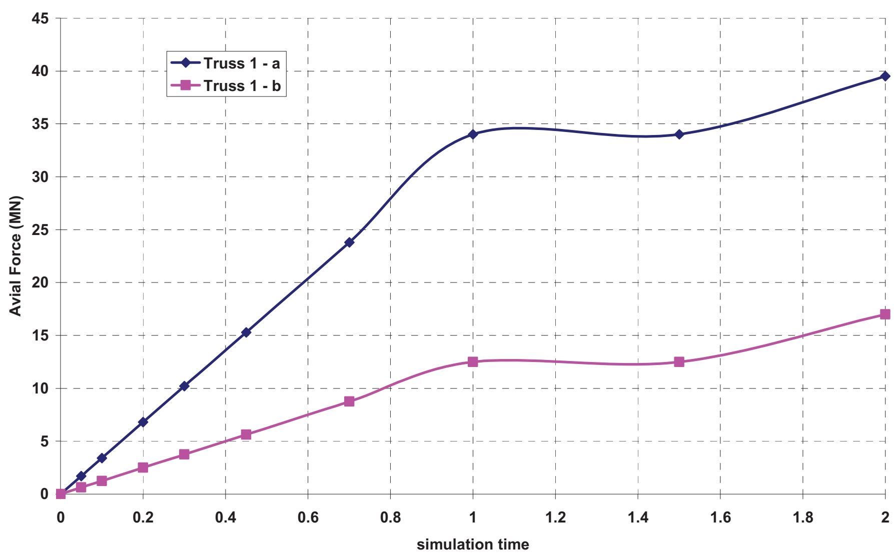


Figure 21 – *The plot shows the increase in axial force in the diagonal members of Truss 1, for gravity loading (0s – 1s) and then as a result of load redistribution following the heating of Column 79 at the 5^{th} to 6^{th} floor (1s – 2s). A similar plot was produced for the east side of Truss 2, where similar load increases were observed.*

5.5. Summary of Elimination Analysis and Scenario Matching

The individual analysis of the different structural elements exposed to a fire indicates the following sequence of events consistent with the visual evidence of WTC-7's collapse:

1. The diesel fuel fire, having originated in the north-east quadrant of the 5^{th} floor, spread to the Mechanical Room and (i) heated the members of Truss 2 that were fully immersed in the room including Columns 77, 80 and the eastern diagonal and (ii) partially heated the members of Truss 1 immersed in the north wall of the Mechanical Room. Such north-east quadrant fires also heated Column 79.

2. If the epicentre of the fire was in the Mechanical Room, as the structural temperatures of the Truss 2 members increased, Truss 2 lost strength and gradually redistributed loads towards Truss 1 and Column 79.

3. In such scenario, the load redistribution towards Truss 1 and Column 79 overloaded these members. The east diagonal of Truss 1, which had the lowest factor of safety, likely failed first and resulted in the subsequent failure of Column 79. This was manifested visibly as the sinking of the East Penthouse.

4. If the epicentre of the fire was in the vicinity of Column 79, such column, subject to greater heating, would lose strength gradually redistributing the load mainly towards the east side of Trusses 1 and 2, weakened by the heating.

5. In that scenario, load redistributed from failing Column 79 would result in the overloading of weakened Trusses 1 and 2, especially their eastern columns and diagonals, causing their eventual failure. Again, manifested visibly as the sinking of the East Penthouse.

6. The failure of the east side of Truss 2, Column 79 and the east diagonal of Truss 1 resulted in significant load transfer to Columns 73 and 74 as well as the core. This resulted in the observed "kink." Because Columns 73 and 74 were not immersed in the Mechanical Room, they were not directly subject to heating. This explains the delay observed between the sinking of the penthouse and the "kink" created as a result of its failure.

7. As described in [the GNA Global Collapse Report], loss of the eastern region of the building's interior created a large area of laterally unbraced perimeter frame and activated the disintegration of the floor slabs at the western trench headers leading to the global collapse.

6. Application of the Fire

After establishing the most likely mode of collapse from the elimination analysis described in Section 5, fire and heat transfer analyses described in Sections 3 and 4 were applied to the 15 storey structural model. Three independent analyses were considered: (i) a scenario where all members of Trusses 1 and 2 are equally heated (worst case scenario), (ii) a scenario where only the East side of Trusses 1 & 2 are heated simultaneously; (iii) a scenario where Truss 2 heated up faster than Truss 1. The third scenario was not studied because it is not possible to determine the exact protection that the gypsum wall board and the bricks provided to Truss 1. Nevertheless, given the size of the truss and level of exposure it will be expected that the result will be of similar nature to that considered in scenario (ii).

Figure 22 shows the results of the first scenario where the entire trusses were heated in a homogeneous manner. As it can be seen failure is observed to occur from north to south along the "kink" leading to global collapse. Figure 23 shows the runaway deflections that indicate the onset of global collapse. It is important to note that two graphs are being presented, the results using an implicit solver and those for an explicit analysis. Implicit solvers require the achievement of equilibrium, thus cannot reproduce a runaway failure. An explicit solver reproduces the dynamic equations, thus does not need to achieve equilibrium and can consequently reproduce the runaway failure. It is important to compare the results for both, because the implicit results away from failure validate that the matching explicit solution is going in the right direction.

For this particular scenario, the sinking of the penthouse did not precede the formation of the "kink," thus this level of heating was discarded because it did not match the evidence.

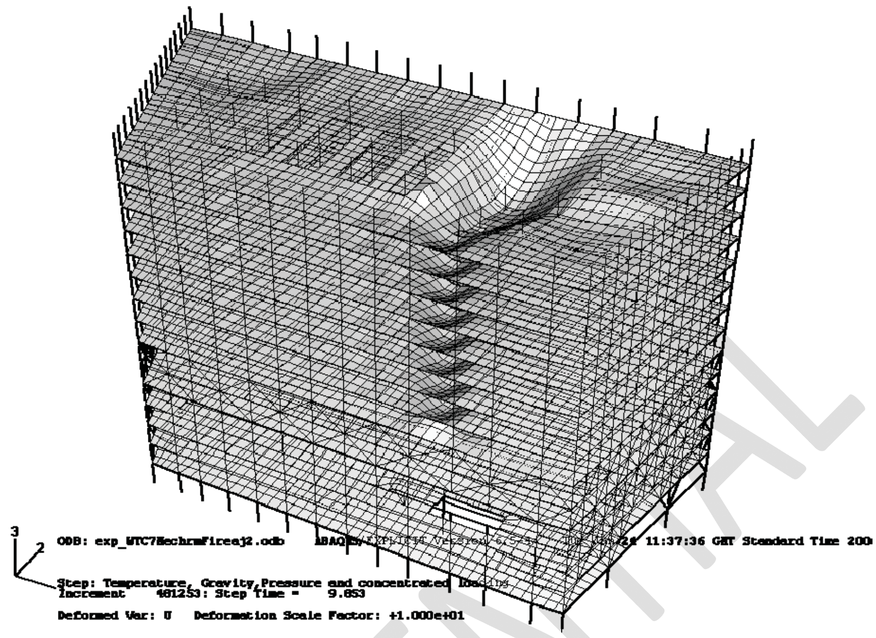


Figure 22 - *Vertical displacements leading to global collapse when Truss 1 and Truss 2 were heated by the fires specified in Sections 3 and 4.*

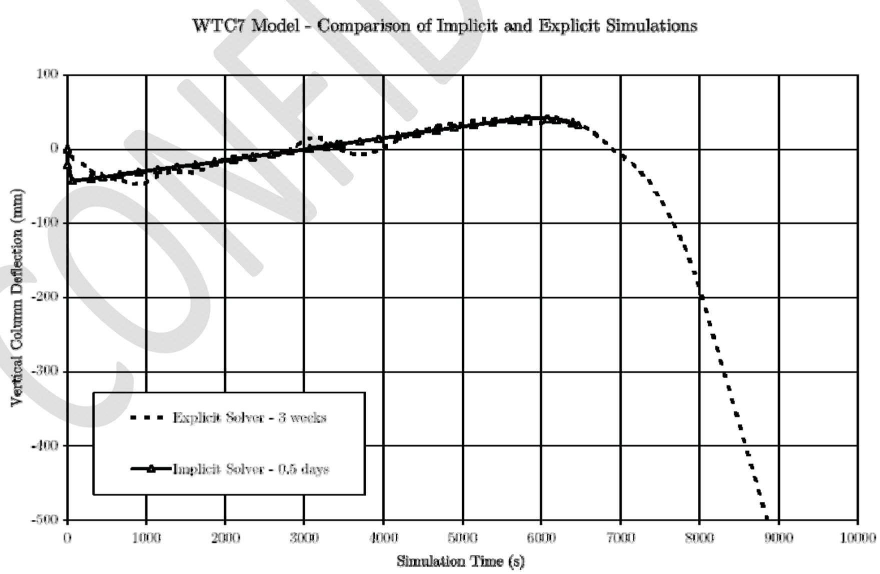


Figure 23 - *Comparison of Implicit and Explicit simulations showing runaway vertical deflections indicating the onset of global collapse.*

The second scenario studied heated the east section of Trusses 1 and 2. The deflection pattern produced (Figure 24) coincided with the footprint of the East Penthouse as well as the kink. This serves to validate this scenario as the most likely collapse sequence. In this analysis the elements were heated simultaneously, it was thus not possible to deduce if the exact time delay between the two characteristic failure events would be reproduced.

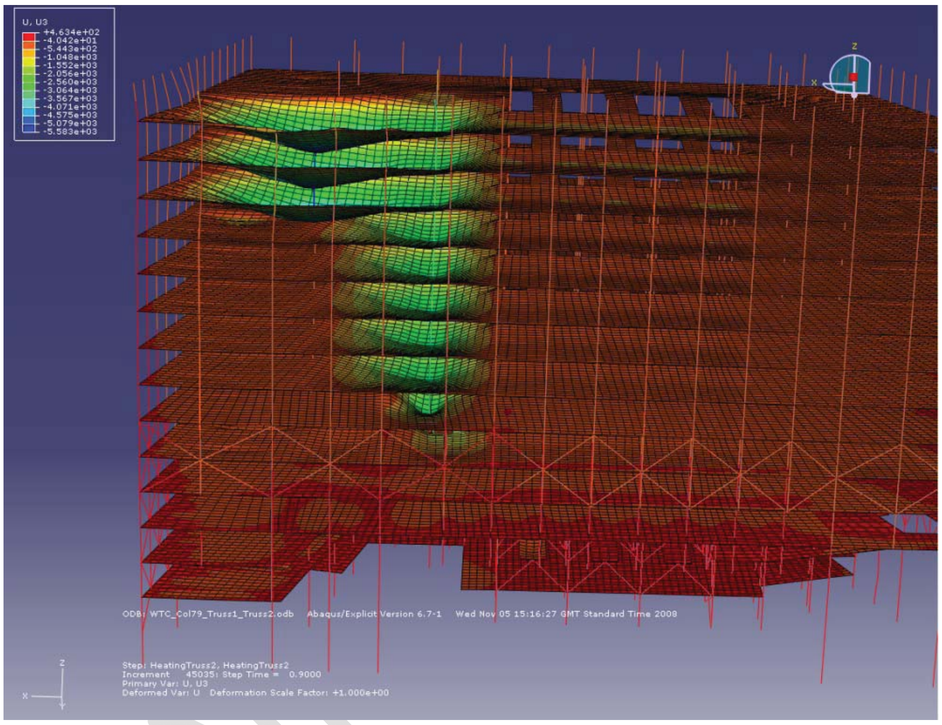


Figure 24 - *Vertical deflections before runaway when the east side of Trusses 1 & 2 were heated with the fire prescribed in Sections 3 & 4.*

The fire scenarios provide a realistic heating rate for the structural elements (see Section 4). Thus it is possible to estimate the period of continuous heating required to reach the failures described in this section. While it is difficult to assess the exact times to failure, some estimates can be made by comparing the temperatures required to attain failure in the models and the prescribed heating curve shown in Figure 10. These estimates are based on punctual failures recorded from the finite element analysis. Table 2 reproduces a set of such failures providing estimates of the heating times required. The times presented include the correction for fireproofing as described in Section 4 (Figure 10).

Location on Element	TRUSS 1	TRUSS 2
TOP (ºC)	703.1	647.9
TOP (K)	976.1	920.9
BOTTOM (ºC)	590.0	540.4
BOTTOM (K)	863.0	813.4
Equivalent Time (sec)	7300 (**2.0**hr)	6687.5 (**1.9**hr)

Table 2 - *Temperature of top and bottom nodes of structural models at failure and equivalent time of exposure to fire.*

7. Conclusions

The analysis set forth in this report leads to the conclusion that the global collapse of WTC-7 would occur due to a diesel fuel fire ignited in the mechanical room, in the north-east quadrant of the $5^{th}/6^{th}$ floors, which would compromise the strengths of Truss 1 and 2 leading to redistribution of loads and failure of such trusses and the columns surrounding them, causing the unbracing of the eastern region and westward spread of the collapse. An alternative mode of failure due to a fire outside the mechanical room in the vicinity of Column 79 would lead to the same global collapse scenario.

8. References

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[6] SFPE Handbook of Fire Protection Engineering, NFPA, SFPE, 4th Edition, 2009.

[7] Exhibit 42 to the February 1, 2010 Second Declaration of Jemi M. Goulian In Support of Plaintiff's Opposition to Defendant's Motion for Summary Judgment.

Other Reference Material

Drawings

- Drawing S1 – First Floor Framing Plan, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985)
- Drawing S2 – Second Floor Framing Plan, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985)
- Drawing S3 – Third Floor Framing Plan, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985)
- Drawing S4 – Fourth Floor Framing Plan, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985)
- Drawing S5 – Fifth Floor Framing Plan, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985)
- Drawing S5A – Fifth Floor Diaphragm Framing Plan, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985)
- Drawing S6 – Sixth Floor Framing Plan, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985)
- Drawing S7 – Seventh Floor Framing Plan, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985)

- Drawing S8 – Typical Floor Framing Plan 8th – 20th and 24th to 45th, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985)
- Drawing S10 – Core Framing Plans 8th to 23rd Floor, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985)
- Drawing S15 – Wind Girder Schedule, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985)
- Drawing S17 – Column Schedule 1, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985)
- Drawing S17a – Column Schedule 2, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985)
- Drawing S18 – Column Schedule 3, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985)
- Drawing S19 – North-South Wind Bracing Elevations, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985)
- Drawing S23 – Truss and Girder Details, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985)
- Drawing 6 – First Floor Plan, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985)
- Drawing 7 – Second Floor Plan, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985)
- Drawing 8 – Third Floor Plan, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985)
- Drawing 10 – Fourth Floor Plan, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985)
- Drawing 11 – Fifth Floor Plan, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985)
- Drawing 12 – Sixth Floor Plan, S*tructural and Architectural Blueprints of World Trade Centre 7*, N.Y. (1985)
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- McAllister, T. et al, *World Trade Centre Building Performance Study,* Technical Report FEMA 403, Federal Emergency Management Agency, Washington D.C., p.1-2,1-4,1-19, (2002)
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- McGrattan, K. et al., *Fire Dynamics Simulator (Version 3-5) – User's Guide*, U.S. Department of Commerce & National Institute of Standards and Technology, U.S.A, (2002-2009)
- Expert Report by Frederick W. Mowrer, Ph.D., Exhibit B: GNA Photographic Analysis Report

Compensation

The above work was charged at a rate of US$ 250.00 per hour.

Appendix 1 -Validation of the rigid connection assumption

Throughout the modelling, beam-to-beam and beam-to-column connections were assumed to be rigid. That is to say that they possess unlimited strength and there is no joint rotation with respect to the connected members. Although this does not precisely represent the actual connection strength/rotation, this assumption is nonetheless appropriate in this modelling as the primary aim is to establish overall structural behaviour and to map possible routes to failure.

In order to validate this assumption, the heated beam axial forces were examined. Figure 25 shows how axial forces in a beam will change through its lifecycle during a fire. The initial condition of a simple structure is shown in (a) before loading. When loading is applied, the beam is in bending (b) but as the beam heats it begins to expand (c) the axial forces become compressive. Finally, as heating progresses and catenary action is seen, there are large tensile axial forces in the beam and at this stage connection failure is likely to occur where the beam pulls away from the connection.

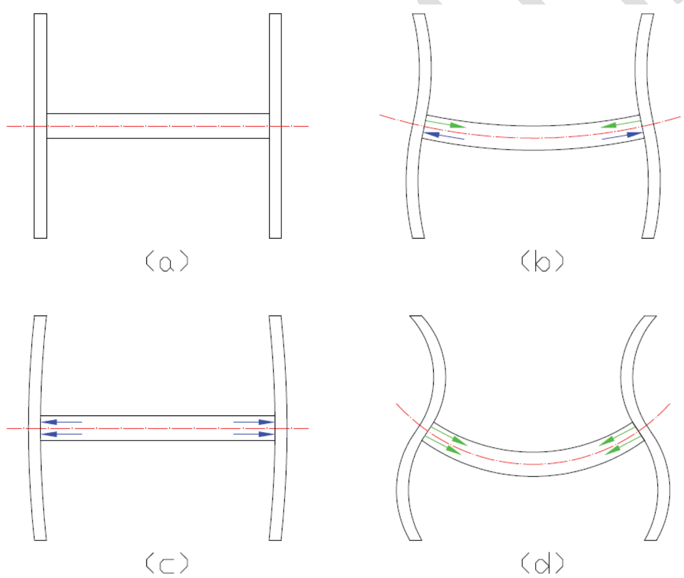

Figure 25 - *Beam axial forces (a) Initial condition (b) Loading (c) Thermal Expansion (d) Catenary Action*

Condition (d) is typically reached late in the heating process. At this stage most of the loads from the weakened structural elements would have been already transferred and therefore the failure characteristics of the structure would have been defined.

As an example to illustrate this point, axial forces were monitored in Truss 2 at the ends of the major elements throughout the simulations to ensure that the infinite connection assumption would hold until after the building behaviour had been established, thus affirming that the findings were valid. The locations and numbering of the elements monitored are shown in Figure 26.

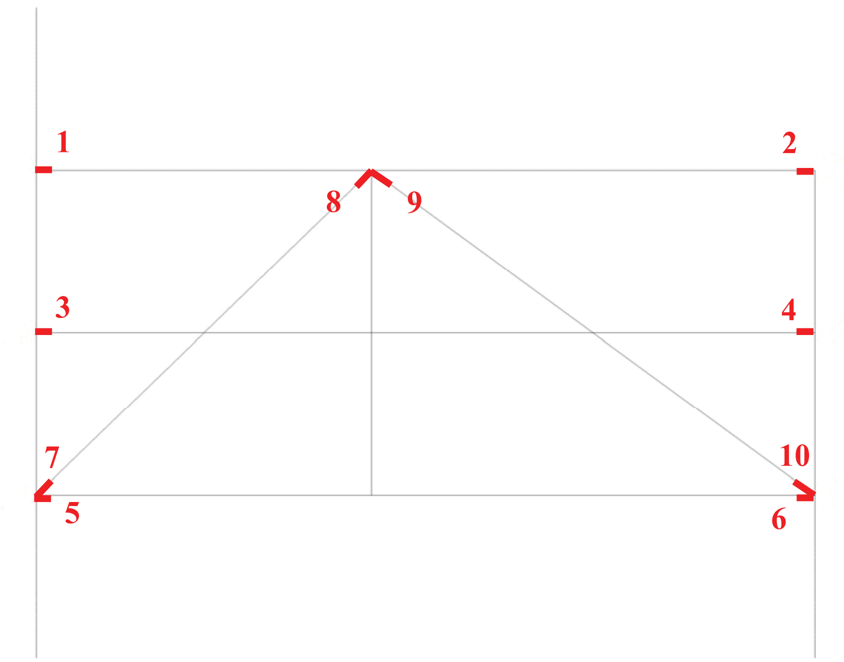

Figure 26 – *The image shows the locations on Truss 2 where the section forces were monitored.*

The results are shown in Figure 27. The axial loads are normalized to their design values (defined as the loading when cold). As it can be observed, those elements under tension undergo a reduction in load as the structural elements thermally expand (positive values), those members under compression (negative) remain under compression until approximately 700°C (973 K). This temperature is already above the typical failure temperatures described in the report. Even when they enter into tension, it will take a significant further increase in temperature before they reach their design values.

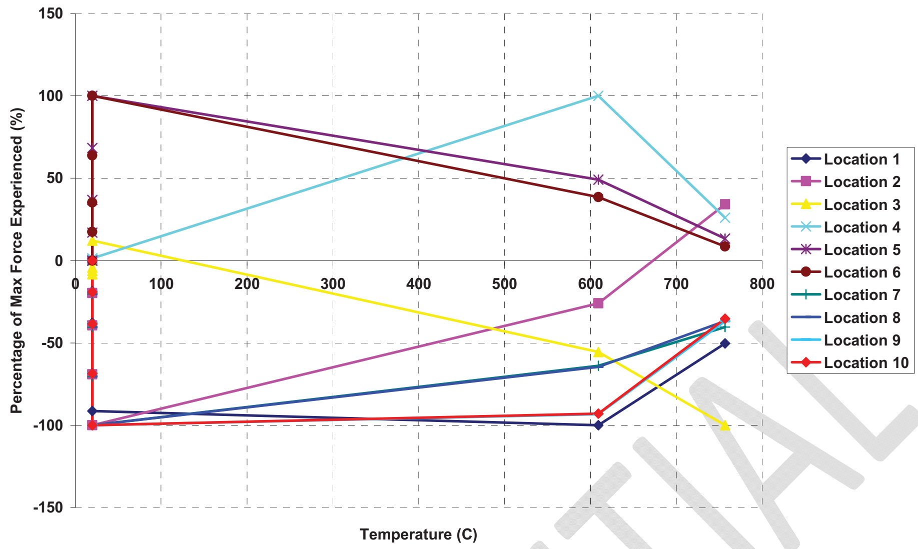

Figure 27 – *Axial forces monitored at the different locations indicated in Figure 26. All forces have been normalized to be 100% at the maximum force experienced – It can be seen that with, the exception of locations 3 and 4, this is always the gravity loading when cold. Thus, failure of the connections is not expected through almost the entire heating period. Locations 3 and 4 experience initially very small loading (0.04kips). As such, although the increase is important it remains significantly below capacity.*

Appendix 2 –CV Torero

José L. Torero, FRSE

BRE Trust/RAEng Professor of Fire Safety Engineering
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Education & Professional Accreditation

Chartered Engineer, Engineering Council Division, UK		(2002)
Ph.D.	University of California, Berkeley	(1992)
M.Sc.	University of California, Berkeley	(1991)
B.Sc.	Pontificia Universidad Catolica del Peru	(1988)

Academic Contributions

Authorship of a book in computational methods for fire safety engineering, more than 20 book chapters and more than 400 technical publications in a broad array of subjects associated to fire safety engineering.

Awards

Elected fellow of the Royal Society of Edinburgh and awarded the Arthur B. Guise Medal by the Society of Fire Protection Engineers (USA) in 2008, both in recognition of eminent achievement in advancing the Science of Fire Protection. Appointed to a Research Professorship by the Royal Academy of Engineering in 2004 which is the highest external appointment made by this institution. Received diverse scientific awards such as the NASA-Certificate of Recognition for Outstanding Contributions to Space Shuttle Mission and the Faculty Achievement Award, from the Office of the President of the University of Maryland. Recognised for service to the profession with honorary membership to the Salamander Fire Protection Engineering Honour Society and with the Faculty Service Award, A. J. Clark School of Engineering (University of Maryland). Acknowledged for oral communication with the William M. Carey Award for the Best Paper Presented at the Fire Suppression and Detection Research Application Symposium (2001) and for written communication with the Harry C. Bigglestone Award for the Best Paper Published in Fire Technology in 2002 and 2005, the Bodycote Warrington Fire Research Prize and the FM Global Best Paper Award both in 2007. He was awarded the Lord Ezra Award (2009) for innovation in Combustion Engineering by the Combustion Engineering Association, UK. In 2009 he also received the Best Knowledge Transfer Partnership Award of Scotland from the Scottish Executive. Teaching contributions have been recognised with the Lilly-Center for Teaching Excellence Fellowship, the Outstanding Mentor of the Year Award, the E. Robert Kent Outstanding Teaching Award for Junior Faculty and the Outstanding Teacher Award all at the University of Maryland. Prof. Torero's work bringing technology to the Fire Service was the subject of the April, 2007 BBC Horizon show: "*Skyscraper Fire Fighters*" that has been shown in more than 30 countries.

Academic Experience

Upon completion of doctoral studies and a brief Post Doctoral appointment at NASA Lewis Research Centre (1992), joined the Laboratoire de Chimie et Physique de la Combustion (Poitiers, France) as a European Space Agency Post Doctoral researcher (1993) followed by an appointment as a CNRS Research Scientist at the Laboratoire de Combustion et Detonique (Poitiers, France) until 1995. Directed research programmes in spacecraft fire safety, polyurethane foam fires, compartment fires and tunnel fire spread and smoke control. Placed experiments in 3 Space Shuttle Missions and two sounding rockets.

Joined the Department of Fire Protection Engineering at the University of Maryland (1995-2001) where held the titles of Assistant and Associate Professor and remains as Adjunct Professor. Served also as Affiliate Associate Professor in the Department of Aerospace Engineering. Taught all general and specialty classes in Fire Protection Engineering, continued research in spacecraft fire safety and compartment fires and extended experience to the areas of material flammability, fire suppression, smoke detection and oil spill control. Developed state of the art laboratory facilities and test methods and managed a research group that exceeded twenty people. Research funds in excess of $4 million where raised in this period.

Appointed Reader in Fire Dynamics (2001) and later BRE Trust/ RAEng Professor of Fire Safety Engineering and Director of the BRE Centre for Fire Safety Engineering at the University of Edinburgh (2004). Raised industrial funds for the endowment of two Professorial Chairs, the organization of the BRE Centre for Fire Safety Engineering and state of the art laboratory facilities. Managed research funds in excess of £6 million obtained from government, research councils and industry. Developed a new undergraduate curriculum in Structural Fire Safety Engineering and transformed a reduced group of one permanent staff and one student into a research group of more than 45 members with 9 permanent academic staff. Developed research work in the areas of tunnel fire safety, structural behaviour in fire, material flammability, forest fires, post fire remediation and sensor driven emergency response. Appointed Head of the Institute for Infrastructure and Environment in 2008 (Department Chair). The Institute counts with 45 staff members (22 Academic) and more than 100 PhD students with an overall yearly research budget of more than £3 million.

Appointed to the Advisory Boards of WPI and Glasgow Caledonian University and Adjunct Professor at the University of Cantabria, Spain. Held short time appointments as Visiting professor at the University of Texas at Austin, the University of California San Diego, the University of Bremen (ZARM), Germany, the Catholic University of Santiago, Chile, the Instituto Nacional de Tecnica Aeroespacial (INTA), Spain and the Universities of Poitiers, Paris VI, Bourges, ENSTIB, Ecole de Mines de Saint Etienne, Ecole Polytechnique and Aix-Marseille in France.

Supervised more than 30 M.Sc., 5 completed Ph.D. and 8 current Ph.D. students. Developed numerous short courses taught around the world to professionals in fire investigation, fire safety engineering design, building control and the fire service.

Professional Involvement & Affiliations

Active membership in The Institution of Fire Engineers (IFE), American Society of Mechanical Engineers (ASME), American Institute of Aeronautics and Astronautics (AIAA), Combustion Institute, International Association for Fire Safety Science (IAFSS), Society of Fire Protection Engineers (SFPE) and the National Fire Protection Association (NFPA).

Associate Editor of Combustion Science and Technology and member of the Editorial Boards of Fire Technology Journal, Fire Safety Journal, Fire Science and Technology and Progress in Energy and Combustion Science. Colloquium Chair for the 30th and 31st Combustion Symposium and member of the Program Committee for the 8th and 9th International Symposium on Fire Safety Science. Advisor to the National Association for State Fire Marshals (USA), the Scottish Chief Fire Officers Forum, the Office of the Deputy Prime Minister and Vice-Chair of the International Association for Fire Safety Science (IAFSS). Member of the Forum of Chief Fire Officers of Scotland (SDAF) and of the CFOA Training Needs Analysis Gateway Review Group and co-Chair of the Fire safety Working Group of the International Committee on Tall Buildings and Urban Habitat (CTBUH). Member of the Society of Fire Protection Engineers, International Standards Development Committee, Underwriters Laboratory STP-162 Foams Fire Suppression Systems Committee, the American Institute of Aeronautics and Astronautics

(AIAA) Micro-Gravity and Space Processes Technical Committee, the Committee of the British Section of the Combustion Institute and the American Society of Mechanical Engineers, K-11 Committee on Fire and Combustion.

Experience as a Consultant

Member of the Board of Directors of LPP Combustion, LLC (USA), Technical Director for the Building Research Establishment (UK) and for I-Risk (Germany), served as consultant to the Vice-President of Peru (Peru), ESSAC (Peru), DICTUC SA (Chile), IRSN, INERIS and La Police Scientifique de Lyon (France), DVS Risk Services GmbH (Germany), Lurgi Metallurgie GmbH (Germany), Rushbrook Consultants (UK), Ove Arup & Partners (UK), Powerwall (UK), Jacobs Engineering (UK) and Jacobs Babtie (USA), Exponent Inc. (USA), Combustion Science and Engineering (USA), NRC (USA), Packer Engineering (USA), Rolf Jensen and Associates, Inc. (USA), Whirlpool Corporation (USA), and to the World Bank.

Conducted work on prescriptive and performance based design, forensic fire investigation and product development. Conducted detailed structural response to fire, fire resistance evaluation, material selection, life safety analysis, smoke evacuation, detection and alarm design as well as standard and advanced fire suppression systems. Developed projects on transportation centres, hangars, trains and aircraft, industrial facilities, tunnels, high rise buildings, public assembly facilities and historic buildings. Used different codes and standards as well as a comprehensive array of analytical and numerical tools. Conducted third party reviews and supported fire service and building control in the approval process.

Participated in landmark projects like the NASA Space Shuttle Hangars in Florida, the 80 storey Heron Tower in London, the Clyde and Dartford Tunnel fire safety design, the investigations of the WTC 1, 2 and 7 collapses, the Madrid Windsor Tower Fire, the Texas City and Buncefield Explosions as well as the Ycua Bolanos supermarket fire. Currently involved in the safety analysis of several operating nuclear power plants and the decommissioning of others.

Appendix

Lecture Invitations

Invited Conference Lectures

1. J. L. Torero, "Laminar Diffusion Flames Established over a Flat Plate Burner under Micro-Gravity Conditions," *International Workshop on Short Term Experiments under Strongly Reduced Gravity Conditions*, Bremen, Germany, July 1994.

2. J. L. Torero, "Diffusion Flames in Micro-Gravity," *Meeting of the ESA Physical Sciences Working Group*, Berlin, Germany, April, 1995.

3. J. L. Torero, "Numerical Simulation of Flat Plate Ethane-Air Diffusion Flames and Experimental Validation at Different Gravity Levels," *9th European Symposium on Gravity Dependent Phenomena in Physical Sciences*, Berlin, May 1995.

4. J. L. Torero, "The Emmons Problem: Experimental Results and Progress Leading to a MiniTexus Experiment," *ESA-Sounding Rocket Experiments Workshop*, ESTEC, Noordwijk, The Netherlands, September 1998.

5. J. L. Torero, "Material Flammability and Fire Safety," *Society of Fire Protection Engineers*, Chesapeake Chapter, Maryland, September, 1998.

6. J. L. Torero, "La Formation de l'Ingenieur Incendie-Programmes Developpes aux Etats Unis et dans d'Autres Pays," *SFPE Chapitre Francaise*, Les Salons du Grand Louvre, October 1998.

7. J. L. Torero, "Educación en Ingeniería de Protección Contra Incendios," *Primer Foro Regional NFPA*, Lima '99, Lima, Peru, October, 1999.

8. J.L. Torero, "Challenges and Needs in Fire Protection Engineering Research and Education," *European Seminar on Environmental Risks*, Niort, France, October 2000. ***(Keynote)***

9. J.L. Torero, "Cooperation and Student Exchange Between the University of Maryland and French Higher Education Institutions," *Global E3 Annual Meeting*, Lake George, New York, June 2001. ***(Keynote)***

10. J.L. Torero, "The Mass Transfer Number as a Criterion for Spacecraft Material Flammability," *Workshop on Research Needs in Fire Safety for the Human Exploration and Utilization of Space*, NASA Glenn Research Center, Cleveland, Ohio, June 2001.

11. J.L. Torero, "The Role of Fire Science in Fire Investigation," *Fire Safety and Rescue Asia Conference*, Singapore, November, 2001. ***(Keynote)***

12. Torero, J. L., J. G. Quintiere and T. Steinhaus, "Fire Safety in High-rise Buildings: Lessons Learned from the WTC," 51st *Jahresfachtagung der Vereingung zur Forderrung des Deutschen Brandschutzez e. V.*, Dresden, Germany, 2002. ***(Keynote)***

13. J.L. Torero, "Fire and the Environment," *International Workshop on Environmental Risk Assessment*, Damascus, Syria, October, 2002. ***(Keynote)***

14. J.L. Torero, "Scaling of Micro-gravity Combustion Systems, Implications to Spacecraft Fire Safety" *European Workshop on Micro-gravity Combustion*, Poitiers, France, October 2002. ***(Keynote)***

15. J.L. Torero, "Desarrollo de una Reglamentacion Adecuada en Materia de Seguridad Contra Incendios," *Conference on Fire Safety organized by the Vice-President of the Republic*, Lima, Peru, November 2002. ***(Keynote)***

16. J.L. Torero, "Conclusiones para una Reglamentacion Adecuada en Materia de Seguridad Contra Incendios," *Conference on Fire Safety organized by the Vice-President of the Republic*, Lima, Peru, November 2002.

17. J.L. Torero, "Fire Safety Science in Support of Performance Based Design: Innovation or Just Filling the Gaps?," *The Graduate Lecture*, The Institution of Fire Engineers, Preston, Lancashire, April 2003. ***(Keynote)***

18. J.L. Torero, "Fire Modeling and Fire Performance," *The Rasbash Lecture and ECD Conference*, Ministry of Defence, Whitehall, London, UK, June 2003.

19. J.L. Torero, "La Experiencia del World Trade Center," *Seminario Donde Hubo Fuego, Que Hacemos con las Cenizas*, Santiago, Chile, June 2003. ***(Keynote)***

20. J.L. Torero, "L'Approche des Risques en Europe et aux Etats-Unis," *Colloque Les risques Industriels & Technologiques, Enjeux Internes et Effets Externes, Bourges*, France, October 2003. ***(Keynote)***

21. J.L. Torero and D.D. Drysdale, "Ignition and Flame Spread Studies as they Relate to Material Flammability," *Joint Meeting of the Fire Engineering Research Network (FERN) and the Fire Chemistry Network (FCHEM)*, March, 2004.

22. J.L. Torero, "FireGrid: Data Base Needs," *Digital Library Workshop*, National Institute of Standards and Technology (NIST), Maryland, USA, April 2004.

23. J.L. Torero, "Structures in Fire: An Overview of the Boundary Condition," *Fire And Structures: The Implications of the World Trade Center Disaster Conference*, The Royal Society of Edinburgh, Edinburgh, April, 2004.

24. J.L. Torero, "The Use and Misuse of Fire Modelling" *Society of Fire Protection Engineers*, California Chapter Spring Meeting, Luncheon Speaker, May, 2004.

25. J.L. Torero, "The Risk Imposed by Fire to Buildings and how to Address it," *NATO-Russia Workshop on the Protection of Civil Infrastructure from Acts of Terrorism*, Russian Academy of Sciences, May 2004.

26. J.L. Torero, and T. Steinhaus, "Applications of Computer Modelling to Fire Safety Design," 53rd *Jahresfachtagung der Vereingung zur Forderrung des Deutschen Brandschutzez e. V.*, Essen, Germany, June, 2004. ***(Keynote)***

27. J. L. Torero, "Lecciones Aprendidas Durante el Colapso de las Torres Gemelas en N.Y.," *Primer Congreso Nacional de Seguridad Contra Incendios, NFPA 2004*, Mexico City, November, 2004. ***(Keynote)***

28. J.L.Torero, "Introducción al Diseño Basado en el Desempeño de la Ingeniería Contra Incendios," *Primer Congreso Nacional de Seguridad Contra Incendios, NFPA 2004*, Mexico City, November, 2004.

29. J.L.Torero, "L'évolution du métier Préventeur – Fire Risk Manager" *Salon POLLUTEC*, Lyon, France, November 2004. ***(Keynote)***

30. J.L. Torero, "What is Fire Engineering? Where has it come from and where is it going?" *Developing the Role of Fire Engineering*, Cavendish Conference Centre, London, New Civil Engineering, April 2005.

31. J.L. Torero, "Structural Fire Engineering and Conjugate Heat Transfer," *Fire Bridges*, Belfast, Northern Ireland, May 2005.

32. J.L. Torero, "How can Fire Models Support Fire Reconstruction?" *The Rasbash Lecture and ECD Conference*, Ministry of Defense, Whitehall, London, UK, June 2005.

33. B. Lane, J.L. Torero, A. Usmani, S. Lamont, A. Jowsey, G. Flint, "Structural Fire Response and Collapse Analysis of WTC 1 & 2," *Technical Conference on the Federal Building and Fire Safety Investigation of the World Trade Center (WTC) Disaster*, National Institute of Standards and Technology, Gaithersburg, Maryland, September, 2005.

34. J.L. Torero, "Forensic Fire Investigation," *Fire Risk Management Networking Meeting*, IOSH, Edinburgh, September 2005.

35. J.L. Torero, "Fire-Arguably the Most Destructive Risk a Business Faces-Do We Understand this Risk? Are We Protected Adequately?" *AEOLUS*, Edinburgh, October, 2005.
36. J.L. Torero, "Heat and Mass Transfer in Fires: Scaling Laws and their Application" *12emes, Journees Internationales de Thermique*, Tangiers, Morocco, November 2005. ***(Keynote)***
37. J.L. Torero, "Structures and Fire – Modern Techniques in Building Design," *Institution of Engineers of Brazil*, Sao Paulo, Brazil , November 2005. ***(Keynote)***
38. J.L. Torero. "Smoke and Fire Detection," *Meeting of the GDR Feux*, ENSMA, Poitiers, January, 2006.
39. J.L. Torero "La Seguridad Contra Incendios en las Edificaciones: ¿Responsabilidad de Ingenieros o de Arquitectos? *International Conference to Celebrate the 10th Anniversary of the Polytechnic University of Puerto Rico*, Overcoming Fire: Architecture and Engineering Solutions, Puerto Rico, February 2006. ***(Keynote)***
40. J.L. Torero "The NIST Report: What are the Future Design Implication for High Rise Buildings," *Designing for Fires in the UK: Can we learn from the NIST Report?*, Institution of Civil Engineers, London, March 2006.
41. J.L. Torero "High Power Computing Solutions for Fire," National Science Foundation, *NSF Workshop on Cyber-based Combustion Science*, Washington D.C., USA, April 2006.
42. J.L. Torero "Questions Liées à la Formation et à l'Entraînement des Personnes Avant, Pendant et Après la Crise," *Stop Feux*, Marseille, May 2006.
43. J.L. Torero, "Post-Flashover Numerical Modelling," *FDS Global Seminar*, Ove Arup and Partners, London, May 2006.
44. J.L. Torero, "Métodos de Protección Pasiva, Análisis Critico y Tendencias," *Seminario de Innovación en el Diseño y Protección de Estructuras contra Incendios*, Santiago de Chile, July, 2006. ***(Keynote)***
45. J.L. Torero, "Emergency Response for Fires: Sensors, Fire Fighters or Both," *Royal Academy of Engineering Research Forum*, September 2006.
46. J.L. Torero, "Te Risk Imposed by Fire to Tall Buildings, What is the State of the Art?," *International Conference on Fire Safety in Tall Buildings*, Santander, October 2006. ***(Keynote)***
47. J.L. Torero, "Sensor Driven Emergency Response for Fires, FireGrid," *Distinguish Lecture Series in Mechanical Engineering, University of Texas at Austin*, October 2006.
48. J.L. Torero, "Fire Safety Engineering: Science or Regulation?" *IRSN Conference on Fire Research and Applications*, Lyon, France, December 2006. ***(Keynote)***
49. J. L. Torero, "Industrial Needs, New Regulation, Existing Knowledge and Available Training in Structural Fire Safety Engineering: Harmony or Chaos?" *IStructE-Seminars*, Royal Society of Edinburgh, Edinburgh, January 2007.
50. J.L. Torero, "Fire dynamics and Building Design," *Western Society of Engineers Annual Meeting*, Chicago, Illinois, USA, May 2007. ***(Keynote)***
51. J.L. Torero, "The Challenge of Interpreting Material Flammability Tests," 11th European meeting on Fire Retardant Polymers, Bolton, UK, July 2007. ***(Keynote)***
52. J.L. Torero, "How Does Academic Research Benefits Stakeholders in the Fire Engineering Disciplines," *Institution of Fire Engineers Annual General Meeting*, Extending the Boundaries of Fire Engineering, Cambridge, July 2007.
53. J.L. Torero, "Emergency Response Post-Terrorist Induced Fire: The Need for Physically based Support Tools," *NATO Advanced Research Workshop*, Urban Structures Resilience under Multi-Hazard Threats: Lessons of 9/11 and Research Issues for Future Work, Moscow, July 2007.

54. J.L. Torero, “Comportamiento Frente al Fuego de Materiales y Elementos de la Construcción,” 2do Encuentro de la Asociación Latino-Americana de Laboratorios de Ensayos de Fuego,” Buenos Aires, Argentina, August 2007. ***(Keynote)***
55. J.L. Torero, “Heat and Mass Transfer in Fires: Scaling Laws and their Application,” *10th UK National Heat Transfer Conference*, Edinburgh, September 2007.
56. J.L. Torero, “Fire Prevention and Fire Suppression: What Makes Fire Different in Spacecraft,” *Association of Space Explorers – The ASE Planetary Congress*, XX Congress, Edinburgh, UK, September 2007.
57. J.L. Torero, “Ingeniería de Protección Contra Incendios: Orden o Caos,” *Segundo Congreso NFPA República Dominicana*, Santo Domingo, Dominican Republic, September 2007. ***(Keynote)***
58. J.L. Torero, “Structural Fire Engineering: A New Design Paradigm,” SFPE Professional Development Conference and Exposition, Las Vegas, Nevada, USA, October 2007. ***(Keynote)***
59. J. L. Torero, “Role of Research In Supporting Developments in Fire Safety and Property protection,” BRE Conference on Fire Safety, November, Garston, 2007. ***(Keynote)***
60. J.L. Torero, “Fundamentos de Ingeniería de Protección Contra Incendios,” Instituto Nacional de Defensa Civil, February, Lima, Perú, 2008.
61. J.L. Torero, “The Dalmarnock Fire Tests: New Findings in High Rise Fire Safety,” Chicago Commission on High Rise Buildings, Dinner Speaker, March 2008.
62. J.L. Torero, “Acciones a tomar por la empresa para prevenir riesgos y su papel en la sociedad para prevención,” Prevención y Atención de Desastres en la Empresa Privada, Cámara de Comercio Peruano Británica, Lima, Perú, August 2008.
63. J.L. Torero, “Estrategias y Conceptos de Protección Contra Incendios: Instalaciones Contemporáneas y Futuras,” 2nd Latin American Conference on Fire Protection Engineering, Lima, Peru, August 2008.
64. J. L. Torero, “Ingeniería de Protección Contra Incendios: Responsabilidad de Ingenieros o de Arquitectos,” Buenos Aires International Security Exhibition & Conference, BISEC, August 2008.
65. J. L. Torero, “The Concepção de Prédios Altos (Arranha-Céus):O Comportamento de Estruturas ao Fogo,”10º Seminario “Tecnología de Estructuras: proyecto y producción con foco en la racionalización y calidad” SindusCon SP, Hotel Grand Hyatt, Sao Paulo, Brazil, August 2008.
66. J. L. Torero, “Fire Protection Engineering: Quo Vadis?” Arthur B. Guise Medal Lecture, Society of Fire Protection Engineers, Annual Meeting, Charlotte, North Carolina, October 2008. ***(Keynote)***
67. J. L. Torero, “Fire Investigation Beyond Cause and Origin,” Chief Fire Officers Association – Scotland, Conference on Forensic Fire Engineering, Glasgow, November 2008.
68. J. L. Torero, “High Stakes and High Rise Fire Safety: Building Design and Fire Liability,” Defence Research Institute, Fire and Casualty Seminar, Marriott Chicago Downtown, Chicago, Illinois, USA, November 2008.

Invited Talks

1. J. L. Torero, “The Effect of Buoyancy on the Geometry of Laminar Diffusion Flames Established Over a Flat Plate Burner,” Borwn Bag Seminar Series, Department of Mechanical Engineering, *The University of Texas at Austin*, Texas, U.S.A., February, 1995.

2. J. L. Torero, "Buoyancy Effects on Smoldering of Polyurethane Foam," BFRL Lecture Series, National Institute of Standards and Technology, Gaithersburg, Maryland, U.S.A. December, 1995.
3. J. L. Torero, "The Role of Micro-Gravity Experiments on Spacecraft Fire Safety," Serie Annual de Conferencias, Escuela Tecnica Superior de Ingenieros Aeronauticos, Madrid, Spain, January, 1998.
4. J. L. Torero, *Material Flammability Studies for Micro-Gravity Environments*, BFRL Lecture Series, National Institute of Standards and Technology, Gaithersburg, Maryland, U.S.A., October 1998.
5. J. L. Torero, "Seguridad Contra-Incendios en Naves Espaciales - Combustion en Micro-Gravedad," Serie de Conferencias Distinguidas de la Escuela de Ingenieros, *Pontificia Universidad Catolica de Chile*, Santiago, Chile, November 1998.
6. J. L. Torero, "Combustion et Securite d'Incendie," Seminaire du LCD, *Ecole National Superieure de Mecanique de d'Aerotechnique*, Poitiers, France, February, 1999.
7. J. L. Torero, "Energy Release Rate: Determination and Application," Danish Technical University, March, 2000.
8. J.L. Torero, "Flammability Criteria Relevant to Material Selection for Spacecraft Applications" Department of Mechanical and Aerospace Engineering Combustion Seminar Series, Princeton University, April, 2000.
9. J.L. Torero, "Ignition Signatures of a Smolder Reaction in Polyurethane Foam," IUSTI Marseille, France, July 2000.
10. J.L. Torero, "Fire Protection Engineering: Current Accomplishments and Challenges," Ecole National Superieure des Mines de Saint-Etienne, Saint-Etienne, November, 2000.
11. J.L. Torero, "Material Flammability, The Screening of Complex Materials for Complex Applications: The International Space Station," Distinguished Lecture Series in Thermofluid Mechanics, Department of Mechanical Engineering, Purdue University, West-Lafayette, Indiana, March 2001.
12. J.L. Torero, "Material Flammability Assessment for the International Space Station," Union College, Schenectady, New York, April, 2001.
13. J.L. Torero, "El World Trade Center: Algunas Preguntas," Serie de Conferencias Distinguidas de la Escuela de Ingenieros, Pontificia Universidad Catolica de Chile, April 2002.
14. J.L. Torero, "Fire Safety Engineering after September 11th, 2001," Herriot-Watt University, Edinburgh, November 2002.
15. J.L. Torero, "A Case for the Use of the Mass Transfer Number as a Flammability Criterion," Factory Mutual Global, Massachusetts, USA, June 2003.
16. J.L. Torero, "The Role of Fire Safety Engineering in Fire Reconstruction: A Case Study – WTC 1&2," Department of Physics Distinguished Lecture Series, University of Bergen, Norway, September 2003.
17. J.L. Torero, "The Use of Fire Safety Engineering in the WTC Investigation," Stord-Haugesund College, Norway, September 2003.
18. J. L. Torero, "Specialized Studies in Fire Safety Engineering," Packer Engineering, Chicago, March 2004.
19. J.L. Torero, "Fire Safety Engineering Analysis of the WTC Collapse," SFPE Norwegian Chapter, Stord-Haugesund College, Norway, March 2004.
20. J.L. Torero, "The Use of the Mass Transfer Number as a Flammability Criterion for Micro-Gravity Environments," Lecture Series of the Mechanical and Aerospace Engineering Department, University of California, San Diego, May, 2004.

21. J.L. Torero, “Ingenieria de Proteccion Contra Incendios Despues del 11 de Septiembre del 2001,” Pontificia Universidad Catolica de Chile, Septembre 2004.
22. J.L. Torero, “Comportamiento al Fuego de Estructuras en Madera,” Pontificia Universidad Catolica de Chile, June 2005.
23. J.L. Torero, “Tecnicas Modernas de Ingenieria de Proteccion Contra Incendios,” Pontificia Universidad Catolica del Peru, November 2005.
24. J.L. Torero, “Fire Safety Engineering in Modern Cities – Design, Prevention and Response,” Joint Meeting of the Fire Brigades, Sao Paulo, Brazil, November 2005.
25. J.L. Torero, “Fire and Combustion,” Pontificia Universidad Catolica, Rio de Janeiro, Brazil, November 2005.
26. J.L. Torero, “FDS: The Good, the Bad and the Ugly,” L’Institut de Radioprotection et Sûreté Nucléaire, Cadarache, France, February 2006.
27. J.L. Torero, “Smoke Properties Affecting Fire Detection,” L’Institut de Radioprotection et Sûreté Nucléaire, Cadarache, France, February 2006.
28. J.L. Torero, “Fire problems for which we can not solve the Maths,” School of Mathematics Colloquium Series, May 2006.
29. J. L. Torero, “Emergency Response Assisted by Data,” Heriot Watt University, November 2006.
30. J.L. Torero, “Sensor Driven Emergency Response: FireGRID,” University of Ghent, March 2007.
31. J. L. Torero, “Modelling of Cone Calorimeter Behaviour,” Predicting the Fire behaviour of Nano-Composites, Bolton, UK, July 2007.
32. J.L. Torero, “Fire Investigation Beyond NFPA 921,” Packer Engineering Inc., Naperville, Illinois, USA, July 2007.
33. J.L. Torero, “Ingeniería de Protección Contra Incendios Más Allá de las Pruebas Estándar y la Regulación,” 2do Encuentro de la Asociación Latino-Americana de Laboratorios de Ensayos de Fuego,” Buenos Aires, Argentina, August 2007.
34. J.L. Torero, “Análisis de la Protección Contra Incendios de un Túnel: El Caso del Túnel de Dartford,” 2do Encuentro de la Asociación Latino-Americana de Laboratorios de Ensayos de Fuego,” Buenos Aires, Argentina, August 2007.
35. J.L. Torero, “Modern Methods in Fire and Explosion Investigation,” Pressure Release, Fires and Explosions, Thermofluid Modelling and Simulation, IMechE, London October 2007.
36. J.L. Torero, “Materiales de Construcción y la Protección Industrial,” 7mo Seminario de Ingeniería de Protección Contra Incendios, Santiago, Chile, October 2007.
37. J. L. Torero, “Fire Research at the University of Edinburgh, An Overview,” Seminar on the Japanese Center of Excellence for Fire Safety Science and Developing a Global Fire Research Network, Kingston University, London, UK, December 2007.
38. J.L. Torero, “Modern Methods in Fire and Explosions Investigation,” Fire Service Fire Investigation Forum, Edinburgh, January 2008.
39. J. L. Torero, “Sistemas de Alarma y Detección de Incendios en Terminales Aéreos,” Seminario de Medio Ambiente y Salud Ocupacional, Lima Airport Partners, June, 2008.
40. J. L. Torero, “Sistemas de Control y Extinción de Incendios en Aeronaves Comerciales,” Seminario de Medio Ambiente y Salud Ocupacional, Lima Airport Partners, June, 2008.
41. J. L. Torero, “Seguridad contra incendios en las edificaciones modernas,” Universidad Peruana de Ciencias Aplicadas, June 2008.

42. J.L. Torero, "Conceptos de Protección Contra Incendio en Túneles e Instalaciones Subterráneas," 2nd Latin American Conference on Fire Protection Engineering, Lima, Peru, August 2008.
43. J.L. Torero, "Comportamiento de las Estructuras durante un Incendio," 2nd Latin American Conference on Fire Protection Engineering, Lima, Peru, August 2008.
44. J.L. Torero, "INDECI: Exigencias e Implementación de la Protección Contra Incendios," 2nd Latin American Conference on Fire Protection Engineering, Lima, Peru, August 2008.
45. J. L. Torero, "Edificios Complejos, Método Normativo o Diseño a base de Desempeño," Buenos Aires International Security Exhibition & Conference, BISEC, August 2008.
46. J. L. Torero, "WTC Have Lessons Been Learnt?"Institution of Civil Engineers, Graduates and Students Committee, The University of Edinburgh, October 2008.

Publications

Books

1. Alvear, D. Capote, J.A., M. Lazaro, Abreu, O.V., Rein, G. and Torero, J.L. "Modelado y Simulación Computacional en la Edificación," Díaz de Santos Eds., pp. 336, 2007.

Chapters in Books

1. H.Y. Wang, J.L. Torero, L. Bonneau and P. Joulain, "Numerical Simulation of Ethane-Air Diffusion Flames Established over a Flat Plate Burner: Comparison with Different Gravity Experiments," *Transport Phenomena in Combustion,* S.H. Chan Editor, **2**, Taylor and Francis Publishers, 1141-1152, 1996.
2. J. L. Torero, H. Y. Wang, P. Joulain and J. M. Most "Flat Plate Diffusion Flames: Numerical Simulation and Experimental Validation for Different Gravity Levels," *Lecture Notes in Physics*, Ratke, L. Walter, H. and Feuerbacher, Eds., Springer-Verlag, **464**, 401-408, 1996.*(Invited & Refereed)*
3. J. T'ien, H-Y. Shih, C-B. Jiang, H.D. Ross, F.J. Miller, A.C. Fernandez-Pello, J.L. Torero and D. C. Walther, "Mechanisms of Flame Spread and Smolder Wave propagation," Fire in Free Fall: Micro-Gravity Combustion, H. Ross, Editor, Academic Press Chapter 5, pp.299-418, 2001.
4. J.L. Torero, "The Risk Imposed by Fire to Buildings and how to Address it," The Protection of Civil Infrastructure from Acts of Terrorism, NATO Advanced Science Institute series, Kluwer Academic Publishers, Frolov and Becker Eds. Pp. 37-56, 2006.
5. C. Lautenberger, J.L. Torero and A.C. Fernandez-Pello, "Considerations for Material Flammability," Chapter 2, *Flammability Testing of Materials in Building, Construction, Transport and Mining Sectors*, Apte Editor, Chapter 1, 1-21, 2006.
6. A. Jowsey, S. Welch and J.L. Torero, "Heat and Mass Transfer for Modeling of Structures in Fire," Transport Phenomena in Fire, B. Sunden and M. Faghri Editors, WIT Press, UK, Chapter 4, 2007.
7. J.L. Torero and R. Carvel, "The Dalmarnock Fire Tests: Preface," The Dalmarnock Fire Tests, Rein, Empis & Carvel Eds., 2-6, 2007.
8. S. Welch, A.S. Usmani, R. Upadhyay, D. Berry, S. Potter, J.L. Torero, "Introduction to FireGrid," The Dalmarnock Fire Tests, Rein, Empis & Carvel Eds., 7-30, 2007.
9. C. Abecassis Empis, A. Cowlard, S. Welch and J.L. Torero, "Test One: The Uncontrolled Fire," The Dalmarnock Fire Tests, Rein, Empis & Carvel Eds., 64-82, 2007.
10. A. Cowlard, T. Steinhaus, C. Abecassis Empis and J.L. Torero, "Test Two: The Controlled Fire," The Dalmarnock Fire Tests, Rein, Empis & Carvel Eds., 83-96, 2007.
11. A. Jowsey, J.L. Torero and B. Lane, "Heat Transfer to the Structure During the Fire," The Dalmarnock Fire Tests, Rein, Empis & Carvel Eds., 139-148, 2007.
12. G. Rein, J.L. Torero, W. Jahn, J. Stern-Gottfried, N.L. Ryder, S. Desanghere, M. Lazaro, F. Mowrer, A. Coles, D. Joyeux, D. Alvear, J.A. Capote, A. Jowsey, P. Reszka, "A Priori Modelling of Fire Test One," The Dalmarnock Fire Tests, Rein, Empis & Carvel Eds., 173-195, 2007.
13. W. Jahn, G. Rein and J. L. Torero, "A Posteriori Modelling of Fire Test One," The Dalmarnock Fire Tests, Rein, Empis & Carvel Eds., 196-114, 2007.
14. J.L.Torero, "Flaming Ignition of Solids Fuels," SFPE Handbook of Fire Protection Engineering, 4th Edition, Chapter 2-11, pp. 2-260-2-277, 2008.

15. Jowsey, A., Torero, J.L., Usmani, A. S., Lane, B. and Lamont, S., “Structural fire Design of Tall Buildings in Fire,” *Fire Safety in High Rise Buildings*, VDM Publishing, 2009.

16. Capote, J.A., Alvear, D., Lazaro, M., Espina, P., Fletcher, I., Welch, S. and Torero, J.L., “Analysis of Thermal Fields Generated by natural Fires on the structural elements of Tall Buildings,” *Fire Safety in High Rise Buildings*, VDM Publishing, 2009.

17. Amundarain, A., Torero, J.L., Usmani, A.S., Al-Remal, A.M., “Light Steel Framing in Fire: Challenges for a New Technology,” *Fire Safety in High Rise Buildings*, VDM Publishing, 2009.

18. Usmani, A.S., Flint, G., Jowsey, A., Roben, C. and Torero, J.L., “Collapse Scenarios of WTC 1 & 2 with Extension to Generic Tall Buildings,” *Fire Safety in High Rise Buildings*, VDM Publishing, 2009.

19. J.L. Torero, “The Risk Imposed by Fire to High Rise Buildings, Introduction,” *Fire Safety in High Rise Buildings*, VDM Publishing, 2009.

20. J.L. Torero and G. Rein, “Physical parameters affecting Fire Growth,” *Fire Retardancy of Polymeric Materials*, Taylor and Francis, Wilke & Morgan Editors, Chapter 3, pp. 43-74, 2010.

21. S. Welch, J.L. Torero and S. Paul, “Modelling of Fire Growth and Toxic Gas Formation,” Fire Toxicity, Hull and Steck Editors, *(in Press)*, 2010.

Articles in Refereed Journals

1. J. L. Torero, M. Kitano and A. C. Fernandez-Pello, “Opposed Flow Smoldering of Polyurethane Foam,” *Combustion Science and Technology*, **91** (1-3), 95-117, 1993.

2. J. L. Torero, A. C. Fernandez-Pello and D. Urban “Experimental Observations of the Effect of gravity Changes on Smoldering Combustion, ” *AIAA Journal*, **31** (5), 991-996, 1994.

3. J.L. Torero, L.Bonneau, J.M.Most and P.Joulain “The Effect of Gravity on a Laminar Diffusion Flame established over a Horizontal Flat Plate,” *Proceedings of the Combustion Institute*, **25**, 1701-1709, 1994.

4. J. L. Torero, A.C.Fernandez-Pello and M.Kitano “Downward Smolder of Polyurethane Foam,” *Fourth International Symposium on Fire Safety Science,* 409-420, 1994.

5. X. Zhou, J. L. Torero, J. C. Goudeau and B. Bregeon “On the Ignition and Propagation of a Reaction Front Through a Porous Fuel: Application to Mixtures Characteristic of Urban Waste,” *Combustion Science and Technology,* **110-111** (1-6), 123-146, 1995.

6. J. L. Torero and A. C. Fernandez-Pello “Natural Convection Smolder of Polyurethane Foam, Upward Propagation,” *Fire Safety Journal*, **24** (1), 35-52, 1995.

7. L. Audouin, G. Kolb, J. L. Torero and J. M. Most “Average Centerline Temperatures of a Buoyant Pool Fire Obtained by Image Processing of Video Recordings,” *Fire Safety Journal*, **24** (2), 167-187, 1995.

8. J. L. Torero, L. Bonneau, J. M. Most and P. Joulain “On the Geometry of Laminar Diffusion Flames Established over a Flat Plate Burner,” *Advances in Space Research*, **16** (7), 149-152, 1995.

9. L. Audouin, G. Kolb, J.L. Torero and J.M. Most “Response to the Letter by D.Milov Commenting the Paper Entitled: “Average Centerline Temperatures of a Buoyant Pool Fire Obtained by Image Processing of Video Recordings” (F.S.J., 24, 2, 1995),” *Fire Safety Journal*, **24** (4), 361-363, 1995.

10. D. P. Stocker, S. L. Olson, D. Urban, J.L. Torero, D. Walther and A.C. Fernandez-Pello,“Small Scale Smoldering Combustion Experiments in Microgravity,” *Proceedings of the Combustion Institute*, **26**, 1361-1368, 1996.

11. N. Wu, M. Baker, G. Kolb and J. L. Torero "Ignition, Flame Spread and Mass Burning Characteristics of Liquid Fuels on a Water Bed," *Spill Science and Technology Bulletin*, **3** (4), 209-213, 1996.

12. J. L. Torero and A. C. Fernandez-Pello "Forward Smoldering of Polyurethane Foam in a Forced Air Flow," *Combustion and Flame*, **106** (1-2), 89-109, 1996.

13. L. Brahmi, T. Vietoris, P. Joulain and J. L. Torero, "Experimental Study on the Stability of a Diffusion Flame Established in a Laminar Boundary Layer," *Microgravity Abstracts*, **5**, 80-87, 1998. *(in Japanese)*

14. L. Brahmi, T. Vietoris, J. L. Torero and P. Joulain, "Determination par camera Infrarouge des distributions de Temperature sur l'Enveloppe d'une Flamme de Diffusion Etablie sur un Bruleur Poreux Plan en Microgravite," *Enthropie,* **215**, 69-73**,** 1998. *(in French)*

15. N. Wu, G. Kolb and J. L. Torero, "Piloted Ignition of a Slick of Oil on a Water Sublayer: The Effect of Weathering," *Proceedings of the Combustion Institute*, **27**, 2783-2790, 1998.

16. T. Vietoris, J. L. Torero and P. Joulain, "Experimental Characterization of a Laminar Diffusion Flame in Micro-Gravity," *Journal de Chimie Physique,* **96**, 1022-1030, 1999.

17. J. P. Garo, J. P. Vantelon, S. Gandhi and J. L. Torero "Determination of the Thermal Efficiency Pre-boilover Burning of a Slick of Oil on Water," *Spill Science and Technology Bulletin,* **5** (2), 141-151, 1999.

18. L. Brahmi, T. Vietoris, J. L. Torero and P. Joulain, "Estimation of Boundary Layer Diffusion Flame Temperatures by Means of an Infra-Red Camera under Micro-Gravity Conditions," *Measurement Science and Technology*, **10**, 859-865, 1999.

19. R. T. Long, J. L. Torero, J. G. Quintiere and A. C. Fernandez-Pello, "Scale and Transport Considerations on Piloted Ignition of PMMA," *Sixth International Symposium on Fire Safety Science,* 567-578, 1999.

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39. P. Joulain, T. Vietoris and J. L. Torero, "Structure and Stability of a Laminar Flat Plate Difusion Flame in Micro-Gravity," *International Seminar on Micro-Gravity Combustion*, Tokyo, Japan, August, 1999.

40. S. Olenick, M. Roslon, D. Walther, J. L. Torero, A.C. Fernandez-Pello and H. Ross, "Flow Effects on the Microgravity Piloted Ignition Delay of Solid Fuels" *Proceedings of the International Seminar on Microgravity Combustion*, Institute of Fluid Science, Tohoku University, Sendai, Japan, August, pp 172-181, 1999.

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42. J. L. Torero, "Computations and Experiments to Support Fire Investigations: Applying Fire Science in Fire Investigations," *NFPA Fall Meeting*, November, 1999.

43. M. Roslon, S. Olenick, D. Walther, J.L. Torero, A.C. Fernandez-Pello and H. Ross "Microgravity Ignition Delay of Solid Fuels in Low Velocity Flows," Spring Meeting of the Western States Sections, The Combustion Institute, Boulder, Colorado, March 2000.

44. P. Joulain, T. Vietoris, P. Cordeiro, S. Rouvreau, "Etude de la Structure des Flammes de Diffusion Representative des Situationes d'Incendie dans un Environement de Microgravite," *Phenomenes de Transport et Transition de Phase en Micropesanteur*, Grenoble, France, June 2000.

45. J.L. Torero and F.W. Mowrer "A New Approach to Interpreting Ignition Test Data," *31st International Conference on Fire Safety*, Columbus, Ohio, July 2000.

46. P. Joulain, T. Vietoris and J.L. Torero, "Gas-Gas and Gas-Solid Laminar Flat Plate Diffusion Flames in Micro-Gravity: Structure and Stability," *Drop Tower Days*, Bremen, Germany, September 2000.

47. T. Vietoris, P. Joulain and J.L. Torero, "Study of Micro-Gravity Gas-Solid Combustion in a Sounding Rocket," *First International Symposium on Microgravity Research and Applications in Physical Sciences and Biotechnology*, Sorrento, Italy, September 2000.

48. P. Joulain, H.Y. Wang and J.L. Torero, "Modelisation des Incendies: Cas des feu des Parois Horizontales et Verticales," La Combustion et sa Modelisation, Marseille, France, October 2000.

49. C. Worrell, M. Holton, R. Roby, L. Streit and J.L. Torero, "Acoustic Agglomeration and Deposition of Soot in Smoke Detectors, a Method For Determining if a Smoke Detector Alarmed," *NFPA Fire Detection and Suppression Research Application Symposium*, Orlando, Florida, February 2001.

50. S.D. Wollin, N.L. Ryder, F. Leprince, J.A. Milke, F.W. Mowrer and J.L. Torero, "Measurements of Smoke Characteristics in HVAC Ducts," *NFPA Fire Detection and Suppression Research Application Symposium*, Orlando, Florida, February 2001.

51. G. Legros, K. Blase, J.L. Torero and P. Joulain, "Evaluation of a Realistic Mass Transfer Number from Images of an Upward Spreading Flame," 2nd Joint Sections Meeting of the Combustion Institute, March 2001.

52. S.M. Dakka, G.S. Jackson and J.L. Torero, "TGA/MS Studies of Thermal and Oxidative Degradation of Poly(methyl methacrylate), 2nd Joint Sections Meeting of the Combustion Institute, March 2001.

53. S.M. Dakka, G.S. Jackson and J.L. Torero, "On the Effect of Pyrolysis Kinetics on Ignition Delay Times of Poly(methyl methacrylate)," International Mechanical Engineering Congress and Exposition (IMECE), New York, November 2001.

54. S. Rouvreau, H.Y. Wang, P. Joulain and J.L. Torero, "Simulation Numerique Directe sur les feux de Parois sous Gravite Reduite," Colloque Science de la Matiere et Microgravite, ESPCI, Paris, France, May 2001.

55. P. Cordeiro, G. Legros, P. Joulain and J.L. Torero, "Characterisation de la Structure des Flammes de Diffusion de Type Plaque Plane par Differents Methodes optiques (emission Visible et Radicalaire OH et CH, PIV)," Colloque Science de la Matiere et Microgravite, ESPCI, Paris, France, May 2001.

56. G. Legros, P. Joulain and J.L. Torero, "Characterizsation du nom de Mransfert de Masse par des Images Video," Colloque Science de la Matiere et Microgravite, ESPCI, Paris, France, May 2001.

57. P. Cordeiro, P. Joulain, and J.L. Torero, "Characterization of a Laminar Flat Plate Diffusion Flame in Micro-Gravity Using P.I.V., Visible and CH Emissions," *6th International Micro-Gravity Combustion Workshop*, NASA Conference Publication, Cleveland, Ohio, May, 2001.

58. Y.Y. Zhou, D.C. Walther, A.C. Fernandez-Pello, S. Olenick, J.L. Torero and H. Ross, "Experimental and Numerically Predicted Piloted Ignition Delay in Reduced Gravity," *6th International Micro-Gravity Combustion Workshop*, NASA Conference Publication, Cleveland, Ohio, May, 2001.

59. J.A. Milke, F. W. Mowrer and J.L. Torero, " Duct Smoke Detector Research," NFPA World Fire Safety Congress and Exposition, Anaheim, California, May 2001.

60. S.Wolin, N. Ryder, F. LePrince, J. Milke, F. Mowrer and J.L. Torero, NFPA World Fire Safety Congress and Exposition, Minneapolis, Minnesota, May 2002.

61. J.A. Milke, F. W. Mowrer and J.L. Torero, " Duct Smoke Detector Research: Final Report" NFPA World Fire Safety Congress and Exposition, Minneapolis, Minnesota, May 2002.

62. C. Worrell, J. A. Lynch, G. Jomaas, R. J. Roby, L. Streit and J. L. Torero, "Effect of Smoke Source and Horn Configuration on Enhanced Deposition, Acoustic Agglomeration, and Chladni Figures in Smoke Detectors," *NFPA Fire Detection and Suppression Research Application Symposium*, Orlando, Florida, February 2002.

63. S. Rouvreau, H.Y. Wang, P. Joulain and J. L. Torero, "Numerical Simulations of Gas Diffusion Flames in Micro-Gravity on a Flat Plate in a Flow of Oxidizer Parallel to its Surface: Stand-off Distance and Boundary Layer Assumptions," 9th International Symposium on Numerical combustion, Sorrento, Italy, April 2002.

64. T. Rogaume, J. Tezanou, F. Jabouille, and J.L. Torero, "The effects of different combustion regimes on the formation of NO in municipal waste incineration," Joint Meeting of the US Sections of the Combustion Institute, Chicago, March 2003.

65. G. Legros, P. Joulain, J.-P. Vantelon, C. Breillat and J. L. Torero "Comportement Radiatif d'une Flamme de Diffusion se Propageant en Micropesanteur," Congres Française de Mécanique, Nice, France, September 2003.

66. P. Cordeiro, G. Legros, S. Rouvreau, P. Joulain and J. L. Torero, "Detailed Description of the Structure of a Low Velocity Laminar Diffusion Flame in Microgravity," 7th International Workshop on Microgravity Combustion, Cleveland, June 2003.

67. A.C. Fernandez-Pello, D.Rich, J.L. Torero and H. Ross, "Flammability Diagrams of Combustible Materials in Microgravity: Effect of Fiber concentration on Polyethylene," 7th International Workshop on Microgravity Combustion, Cleveland, June 2003.

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69. M. Coutin, A. S. Rangwala, J. L. Torero and S.G. Buckley, "Material Properties Governing Co-current Flame Spread: The Effect of Air Entrainment" 7th International Workshop on Microgravity Combustion, Cleveland, June 2003.

70. R. Carvel, D.D. Drysdale and J.,L. Torero, "Fire Behaviour of Composite Walls," 4th International Seminar on Fire and Explosion Hazards, Londonderry, September 2003.

71. C. Lautenberger, A. Stevanovic, D. Rich, J. L. Torero , A.C. Fernandez-Pello, "An experimental and theoretical study on the ignition delay time of composite materials," *Western States Fall Technical Meeting*, UCLA, Los Angeles California, USA, October 2003.

72. S. Rangwalla, J. L. Torero and S. G. Buckley, "Towards determination of the B number for co-current flame spread using the Fire Dynamic Simulator (FDS) code: Comparison between model and experiment," *Western States Fall Technical Meeting*, UCLA, Los Angeles California, USA, October 2003.

73. C. Lautenberger, A. Stevanovic, D. Rich, J. L. Torero , A.C. Fernandez-Pello, "Effect of Material Composition on Ignition Delay of Composites," *COMPOSITES 2003*

Convention and Trade Show, Composites Fabricators Association, Anaheim, California, USA, October 2003.

74. Usmani, A. S.; Chung, Y. C.; Torero, J. L. "Assessment of the Stability of the WTC Twin-Towers in a Major Fire." Designing Structures for Fire. Proceedings. Society of Fire Protection Engineers and Structural Engineering Institute, Baltimore, MD, September, 2003.
75. G. Legros, J.P. Vantelon, P. Joulain and J.L. Torero, "Influence of the oxidizer velocity on the sooting behaviour of a laminar diffusion flame established in microgravity," International Symposium on Physical Sciences in Space (ISPS), Toronto, May 2004.
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77. S. G. Buckley, A. Rangwala, J.L. Torero, Modeling and analysis of co-current flame spread Applied to the upward burning of PMMA," Workshop on Strategic Research to Enable NASA's Exploration Missions, July, 2004.
78. Roby, R., Klassen, M., Olenick, S. and Torero, J.L., Modelling of Fire Suppression in Spacecraft, Workshop on Strategic Research to Enable NASA's Exploration Missions, July, 2004.
79. Fernandez-Pello, A.C., Rich, D., Lautenberg, C. and Torero, J.L. "Forced Ignition and Spread Test for Microgravity Material Flammability Assessment, Workshop on Strategic Research to Enable NASA's Exploration Missions, July, 2004.
80. A. Jowsey, L.A. Drange and J.L. Torero, "A Case Study on Building Specifications," 5th International Conference on Performance Based Codes and Fire Safety Design Methods in Fire Safety Engineering, Luxemburg, October, 2004.
81. A. Jowsey and J.L. Torero, "Determination of Fire Triggered Collapse Mechanisms of Multi-Storey Steel Framed Structures: A Case Study," Fire Service College Annual Conference (RE04) November 24-25, 2004.
82. A. Fuentes, G. Legros, P. Joulain, J.P. Vantelon and J. Torero, Evaluation of the Extinction Factor in a Laminar Flame Established over a PMMA Plate in Microgravity, Drop Tower Days, Bremen, September 2004.
83. A. Jowsey, J.L. Torero, A. Usmani, S. Lamont and B. Lane, Determination of Fire Triggered Collapse Mechanisms of Multi-Storey Steel Framed Structures: A Case Study, Eurostel, Maastricht, April 2005.
84. G. Flint, A. Usmani, J.L. Torero, S. Lamont and B. Lane, "Analysis of undamaged WTC Twin-Towers structure subjected to large fires", Eurostel, Maastricht, April 2005.
85. G. Rein, A. C. Fernandez-Pello, J. L. Torero and D. L. Urban, "On the Derivation of Polyurethane Foam Kinetics using Genetic Algorithms and its Application to Smoldering," ICCMHT, Paris, May 2005.
86. G. Legros, A. Fuentes, B. Rollin, P. Joulain and J.L. Torero, "Extinction Simulation of a Diffusion Flame Established in Microgravity," ICCMHT, Paris, May 2005.
87. A.S. Usmani, G.R. Flint, Allan Jowsey, Susan Lamont, Barbara Lane and Jose Torero, "Modeling of the collapse of large multi-storey steel frame structures in fire," 4th International Conference on Advances in Steel Structures, Shanghai, June, 2005.
88. A. S. Rangwala and S. G. Buckley and J. L. Torero, "Effects of finite width on upward flame propagation on solid fuels –An experimental study" Western Sates Section, The Combustion Institute, Stanford, California, October, 2005.
89. G. Rein, C. Lautenberger, A. C. Fernandez-Pello, J. L. Torero and D. L. Urban, "Derivation of the Kinetic Parameters of Polyurethane Foam Using Genetic Algorithms, Joint Sections Meeting of The Combustion Institute, Pittsburgh, Pennsilvania, October 2005.

90. Lamont S., Lane B., Jowsey A.I., Flint G.R., Torero J.L., Usmani A.S. Innovative Structural Engineering for Tall Buildings in Fire, JCSS and IABSE Workshop on Robustness of Structures, BRE, Watford, UK, November 2005.

91. A. S. Rangwala and S. G. Buckley and J. L. Torero, “Modelling Upward Flame Spread Using a Time-Varying B-Number,” Western Sates Section, The Combustion Institute, Utah, March, 2006.

92. Olenick, S.M., Roby, R.J., Klassen, M.S., Zhang, W., Sutula, J.A., Worrell, C., Wu, D., D'Souza, V., Ashley, A., Dubois, J., Torero, J.L., and Streit, L., "The Role of Smoke Detectors in Forensic Fire Investigation and Reconstruction," Proceedings of the International Symposium on Fire Investigation Science and Technology (ISFI), Cincinnati Ohio, USA, July, 2006.

93. D. J. Carpenter and R. J. Roby, and J. L. Torero, “Training Versus Education: The Case for the Development of a National Curriculum for Fire Investigators” Proceedings of the International Symposium on Fire Investigation Science and Technology (ISFI), Cincinnati Ohio, USA, July, 2006.

94. D. J. Carpenter and R. J. Roby, and J. L. Torero, “The Use of Toxicity Data in the Reconstruction and Analysis of Fires” Proceedings of the International Symposium on Fire Investigation Science and Technology (ISFI), Cincinnati Ohio, USA, July, 2006.

95. A. Amundarain, J. L. Torero, A. Usmani, A. M. Al-Remal, “Light Steel Framing: Improving the Human-Building Relationship,” GBEN 2006, Preston, UK, September 2006.

96. T. Rogaume, L. Bustamante, F. Richard, E. Guillaume, G. Rein, J.L. Torero, “Caractérisation de la dégradation thermique de matériaux solides : Apports et intérêts”, Groupement De Recherche Feu, Commissariat de l’Energie Atomique, Fontenay aux Roses, December 2006.

97. J. Ferrino-McAllister, R Roby, D. Carpenter and J.L. Torero, “The Extent of Evaporation of Ignitable Liquids Under Exposure to Compartment Fires, Non-Fire Thermal and Non-Thermal Environments**,”** Fire and Materials, San Francisco, January, 2007.

98. L. Bustamante, T. Rogaume, E. Guillaume, F. Richard, G. Rein, J.L. Torero, “Characterizing the Degradation of Solid Materials using the Tubular Furnace, FTIR and Kinetic Modelling”. 21st International Colloquium on the Dynamics of Explosions and Reactive Systems, Poitiers July 2007.

99. P. Reszka, T. Steinhaus, H. Biteau, R. Carvel, G. Rein, J.L. Torero, “A Study of Fire Durability for a Road Tunnel Comparing CFD and Simple Analytical Models”, EUROTUN 2007 Computational Methods in Tunnelling, Vienna, August 2007.

100. C. Switzer, P. Pironi, G. Rein, J.I. Gerhard and J.L. Torero, “Burning Hazardous Liquids in the Soil as a Remediation Technology,” International Meeting of Fire Effects on Soil Properties, Barcelona, February 2007.

Extension Activities and Professional Courses

1. *Fire Phenomena/Enclosure Fires* – Bureau of Alcohol Tobacco and Firearms, Maryland Fire and Rescue Institute, University of Maryland, August 1998.
2. *Control de Riesgos de Incendio* – Pontificia Universidad Catolica de Chile, Santiago, Chile, November 1998.
3. *Feu et Combustion* – Ecole National Superieure de Mecanique et d'Aerothechnique (ENSMA), Universite de Poitiers, France, March 1999.
4. *Seminaire sur le Management des risques d'Incedie,* Univeriste de Poitiers-Site de Niort, France, January, 2000.
5. *Fire Phenomena/Enclosure Fires* – Bureau of Alcohol Tobacco and Firearms, Maryland Fire and Rescue Institute, University of Maryland, August 2000.
6. *Fire Safety* – Masters of Science Loss Prevention and Risk Management, ENSI-Bourges, Bourges, France, November 2000.
7. *Fire Safety* – Masters of Science Loss Prevention and Risk Management, ENSI-Bourges, Bourges, France, December 2001.
8. *Fire Safety Engineering* – Ecole des Mines St. Etienne, St. Etienne, France, January, 2002.
9. *Fire Science and Fire Investigation* – The University of Edinburgh, April 2002.
10. *Performance Based Design of Fire Safety Systems* – Pontificia Universidad Catolica de Chile, June 2002.
11. *Introduction to Fire Safety Engineering,* – Ecole des Mines St. Etienne, St. Etienne, France, February, 2003.
12. *Fire Science and Fire Investigation* – The University of Edinburgh, March 2003.
13. *Fire Dynamics and Fire Safety Engineering Design* - The University of Edinburgh, March 2003.
14. *Ingenieria de Proteccion Contra el Fuego* - Pontificia Universidad Catolica de Chile, June 2003.
15. *Fire Science and Fire Investigation* – The University of Edinburgh, March 2004.
16. *Introduction to Fire Safety Engineering,* – Ecole des Mines St. Etienne, St. Etienne, France, February, 2004.
17. *Concrete Structures in Fire* – Pontificia Universidad Catolica de Chile, September, 2004.
18. *Introduction to Fire Safety Engineering,* – Ecole Polytechnique de Marseille, Marseille, France, September, 2004.
19. *Introduction to Fire Safety Engineering,* – Ecole des Mines St. Etienne, St. Etienne, France, February, 2005.
20. *Timber Construction in Fire*– Pontificia Universidad Catolica de Chile, June 2005.
21. *Primer Seminario de Ingenieria de Proteccion Contra Incendios* – Pontificia Universidad Catolica del Peru, November 2005.
22. *Fire Dynamics and Fire Safety Engineering Design* - The University of Edinburgh, April 2006.
23. *Fire Science and Fire Investigation* – The University of Edinburgh, April 2006.
24. *Seminario de Innovación en el Diseño y Protección de Estructuras contra Incendios*, Santiago de Chile, July, 2006.
25. *Introduction to Fire Safety Engineering,* Ecole Polytechnique de Marseille, November 2006.
26. *Fire Science and Fire Investigation* – The University of Edinburgh, April 2007.

27. *7mo Seminario de Ingeniería de Protección Contra Incendios,* Santiago, Chile October, 2007.
28. *The Dalmarnock Fire Test-1st FireSEAT,* The University of Edinburgh, November 2007.
29. *Fire Safety Engineering Series,* ESSAC, Lima Peru, 2008.

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UNITED STATES DISTRICT COURT
SOUTHERN DISTRICT OF NEW YORK

IN RE: SEPTEMBER 11 PROPERTY DAMAGE AND BUSINESS LOSS LITIGATION	:	21 MC 101 (AKH)
AEGIS INSURANCE SERVICES, INC., et al., Plaintiffs, -against- 7 WORLD TRADE CENTER COMPANY, L.P., et al., Defendants.	:	04 CV 7272 (AKH) **SUPPLEMENTAL AND AMENDED SECOND DECLARATION OF JOSEPH P. COLACO**

I, Joseph P. Colaco, declare:

1. I have been a practicing structural engineer for 44 years and am President of CBM Engineers Inc., Houston, TX. My curriculum vitae is attached hereto as Exhibit A.

2. A list of significant projects with which I had substantial design involvement are as follows:
   100 Story John Hancock Centre, Chicago
   75 Story J. P. Morgan Chase Tower, Houston
   64 Story Williams Tower, Houston
   60 Story Two Prudential Tower, Chicago
   46 Story 101 Park Avenue, New York

3. I have been retained by counsel for Plaintiffs in this case to provide expert analysis with respect to the design/construction issues involved in the collapse of World Trade Center 7 (WTC7) on September 11, 2001.

4. I have reviewed thousands of documents, drawings, and photographs, and have actively participated in and reviewed computer modeling performed on behalf of the Plaintiffs in this case.

5. The opinions expressed herein are based on information I have reviewed thus far, and are subject to amendment if additional materials become available. These opinions and the data and materials relied upon in forming these opinions are more fully set forth in my report dated February 15, 2010, attached hereto as Exhibit B and made a part hereof.

6. However, I can make the statements that follow to a reasonable degree of scientific probability.

7. For the reasons set forth below, and in more detail in my forthcoming expert report, I have concluded that the design and construction of WTC7 deviated from the standard of good engineering practice of world class engineers who design these type buildings and that these deviations caused the global collapse of WTC7.

8. WTC7 was constructed upon a trapezoidal parcel of land.

9. The mirroring trapezoidal shaped WTC7 was constructed to make use of the entire parcel of land upon which it was constructed, creating structural design challenges, which included the use of several cantilevered girders on the north side of the building to span over the already existing Con Edison substation, and the placement of three two-story transfer trusses, to name a few.

10. The corresponding trapezoidal shaped building created angles between beams and girders and girders and columns, which required the construction of non-standard connections. This also necessitated the utilization of skewed connections to create the structural framing surrounding columns 79, 80 and 81.

11. The footprint of WTC7 was substantially larger than the Con Edison substation and substantially larger than the building that was contemplated when the substation was built in 1969.

12. This larger footprint, combined with other factors, resulted in column "discontinuities," meaning that the columns supporting WTC7 did not connect with the columns in the substation. Thus, various kinds of transfers were required to transfer the loads supported by the columns of WTC7 to the ground. In fact, most of WTC 7 was supported by three transfer trusses at floors five to seven.

13. The critical nature of the transfer trusses required that larger factors of safety be used in their construction. The transfer trusses at WTC7 had only a minimum factor of safety built in.

14. Additionally, WTC7 was constructed with extra-large floor bays on the northeast side, which were made possible by constructing the building with few non-perimeter columns. As a result, columns 79, 80 and 81 had large tributary areas and carried enormous loads.

15. The combination of extra large floor bays, transfer trusses, cantilevered girders and unique angles at which beams, girders and columns joined created a building that demanded greater attention to structural integrity, and the ability to resist a disproportionate collapse. No attention was paid to the overall structural integrity of this building.

16. Failure to design and construct a building such as WTC7 with sufficient structural integrity to resist a global collapse, was a deviation from the standard of good engineering practice in existence in the early 1980s.

17. Failure to even consider structural integrity to resist a global collapse in such a building, as the structural engineer did in this case, is a deviation from the most basic engineering principles.

18. Section C26-1001.2 of the NYC Building Code required that columns be braced for 2% of their total compressive design load, on each axis. The bracing of many of the columns in WTC7 did not meet that minimum NYC Building Code requirement. Had all the columns been braced in accordance with that minimum requirement, WTC7 would not have collapsed on September 11, 2001.

19. Upon occurrence of a localized failure, a building properly designed for resistance to disproportionate collapse would have arrested that localized failure and prevented a global collapse.

20. The global collapse of WTC7 occurred as a result of one or more of the following flaws: (1) failure to brace the columns in accordance with the NYCBC requirement that the bracing be able to support 2% of the vertical load carried by the column; (2) failure of the inadequately designed transfer trusses; (3) failure to take into account the issues of structural integrity in any manner in the design/construction of WTC7.

21. Constructing the building with adequate structural integrity could have been achieved at a cost insignificant in relation to the total cost of construction of the building.

I declare under penalty of perjury that the foregoing statements made by me are true. I am aware that if any of the foregoing statements made by me are willfully false, I may be subject to punishment.

Joseph P. Colaco

JOSEPH P. COLACO

DATED: April 1, 2010

JOSEPH P. COLACO
President

EDUCATION

Ph.D./Civil Engineering - University of Illinois, 1965
M.S./Civil Engineering - University of Illinois, 1962
B.S./Civil Engineering - University of Bombay, 1960

REGISTRATIONS & MEMBERSHIPS

Registered Professional Engineer:
Illinois, Georgia, Texas, Missouri, Tennessee, Colorado, California (Civil), California (Structural Authority), Florida, Mississippi, Massachusetts, Indiana, Louisiana, Maryland, Virginia, North Carolina, Minnesota, Washington, D.C., Utah

Memberships:
Fellow, Institute of Structural Engineers (United Kingdom), National Academy of Engineering, American Concrete Institute, American Society of Civil Engineers, American Institute of Steel Construction, Structural Engineers Association of Texas, National Society of Professional Engineers, Texas Society of Professional Engineers

EXPERIENCE

1975/Present: CBM Engineers, Inc. (formerly Colaco Engineers, Inc.):
Partner in Charge, project sampling:

Burj Dubai Peer Review/Value Engineering	Dubai, UAE
Hircon Tower, Dubai Marina	Dubai, UAE
Wachovia Corporate Headquarters	Winston Salem, N. Carolina
Lake Robbins Bridge	The Woodlands, Texas
Gannett Headquarters	Mc Lean, Virginia
Menara Bakrie	Jakarta, Indonesia
Guoman Hotel/Office Building	Kuala Lumpur, Malaysia
Norwest Bank	Minneapolis, Minnesota
NationsBank Plaza	Atlanta, Georgia
One Detroit Center	Detroit, Michigan
Texas Commerce Tower	Houston, Texas
Two Prudential Plaza	Chicago, Illinois
RepublicBank Center	Houston, Texas
AAM Tower	Dubai, UAE
Williams Tower	Houston, Texas
One Ninety One Peachtree	Atlanta, Georgia
Barnett Plaza	Tampa, Florida
Barnett Center	Jacksonville, Florida

12/12/97

Plaza 7	Minneapolis, Minnesota
One Congress Plaza	Austin, Texas
Greyhound Tower	Phoenix, Arizona
100 North Tampa	Tampa, Florida
Wortham Theater Center	Houston, Texas
Four Leaf Towers	Houston, Texas
Four Oaks Place	Houston, Texas
Tocumen International Airport	Republic of Panama
Texas Commerce Center	Houston, Texas
Interfirst Plaza	Houston, Texas
101 California	San Francisco, California
100 Spear	San Francisco, California
33 New Montgomery	San Francisco, California
Methodist Hospital, Dunn Tower	Houston, Texas
Marquette General Hospital	Marquette, Michigan
United Bank Center	Denver, Colorado
1600 Smith at Cullen Center	Houston, Texas
Miami Center	Miami, Florida

1969/1975: Ellisor Engineers, Inc., Houston, Texas
Director of Design and Computer Operations, project sampling:

Memorial Hospital Southwest	Houston, Texas
Stephen F. Austin Coliseum	Nacogdoches, Texas
Houston Central Library	Houston, Texas
Pennzoil Place	Houston, Texas
Dresser Tower	Houston, Texas
One Allen Center	Houston, Texas
101 Marietta	Atlanta, Georgia
Intercontinental Hotel	Dubai, U.A.E.

1965/1969: Skidmore, Owings & Merrill, Chicago, Illinois
Senior Structural Engineer and Participating Associate, project sampling:

John Hancock Center	Chicago, Illinois
One Shell Plaza	Houston, Texas
Two Shell Plaza	Houston, Texas
The Spectrum Sports Arena	Philadelphia, Pennsylvania
500 N. Michigan Avenue	Chicago, Illinois
Chicago Transit Authority 14 stations pedestrian and bus bridges	Chicago, Illinois

1960/1961: Shalimar Tar Products, Ltd., Bombay, India

Prestressed Concrete Experience

RESEARCH	Solar Energy Lunar Colony
COMMITTEE WORK	Board of Directors of Wind Engineers Research Council (WERC), 1990 - 1993
	ASCE: Committee on Composite Construction, Chairman 1991 - 1994
	ASCE: Committee on Wind Effects
	ASCE: Task Committee on Structural Damping Systems
	ACI: Committee on Mat Foundation, Committee 336
	CONSTRUCTION INDUSTRY COUNCIL OF HOUSTON: Committee on Proposed Changes to the Houston Building Code; Member
ACADEMIC	Former Member of Advisory Council, Rice School of Architecture, Rice University
	Former Board Member, Rice Design Alliance (1983 - 1989)
	Former Member of Advisory Council, George R. Brown School of Engineering, Rice University, 1986 to 1998
	1970/Present: University of Houston, Houston, Texas; lecturer/professor in the College of Architecture
	1976/1997: Rice University, Houston, Texas; lecturer of Architecture on part-time basis
	1968/1969: Illinois Institute of Technology, Chicago, Illinois; lecturer
	1966/1968: University of Illinois, Chicago Circle Campus; lecturer
	1961/1965: University of Illinois, Urbana, Illinois; research assistant
AWARDS	Texas Section, American Society of Civil Engineers Award, 1968
	Engineering News Record Award, "Men Who Made Marks in 1973"
	American Institute of Steel Construction - Special Citation Award, 1973 Honor Member of Chi Epsilon, University of Illinois Chapter, 1979
	Fellow, American Concrete Institute, October, 1982
	Annual Award for Outstanding Professional, 1982, presented by the India Culture Center, Houston, Texas, March, 1983

Maurice Van Buren Award for Outstanding Structural Engineering in a Completed Concrete Building project, ACI, March 23, 1983; Los Angeles

Fellow, Institute of Structural Engineers, United Kingdom, 1994

Member, National Academy of Engineering, 1994

Distinguished Alumnus, Civil Engineering, University of Illinois

Distinguished Alumnus, College of Engineering, University of Illinois

JURIES

Associated General Contractor's - 1993 Building Design Awards

International Association of Foundation Drilling, 1991 - Outstanding Drilled Foundation Award

American Society of Civil Engineers, 1991 - 1993 - Society Awards for Most Meritorious Papers

American Institute of Steel Construction - 1990 Architectural Awards of Excellence

Cornell University - Senior Engineering Project, 1990

General Motors - Manufacturing Plant for the 21st Century - ACSA, June 1987

Various juries in connection with teaching work at the University of Houston and Rice University

PUBLICATIONS, REPORTS & LECTURES

"Prediction of Steel Force Distribution in Reinforced Concrete Members from Bond/Slip Characteristics," PhD Dissertation, University of Illinois, 1965.

"Behavior of Splices in Beam-Column Connections," Structural Division, American Society of Civil Engineers (ASCE), October 1967.

"Computer Design of 100-Story John Hancock Center," Structural Division, ASCE, December 1966.

"Analysis and Design of 715' High One Shell Plaza in Houston," Texas Section, ASCE, April 1968.

"End Moments for Floor Beams Framing into Spandrels," American Concrete Institute (ACI) Journal, January 1971.

"Analysis of Transfer Girder Systems," ACI Journal, 1971.

"A Stub-Girder System for Steel Floors in High-Rise Buildings," American Institute of Steel Construction (AISC), July 1972.

"Large Scale Concentration and Conversion of Solar Energy," by A. F. Hildebrant, G. M. Haas - Department of Physics, University of Houston; and by W. R. Jenkins, J. P. Colaco, College of Architecture, University of Houston, April 1972.

"Pennzoil Place - A New Slant in Structural Systems," by P. V. Banavalkar and J. P. Colaco; presented to ASCE-IABSE Regional Conference on Tall Buildings, Bangkok, Thailand, January, 1974 (published in the proceedings).

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"Partial Tube Concept for Mid-Rise Structures," Engineering Journal, AISC, Vol. II, No. 4, 1974.

"The World: The Limit of our Resources;" Seminar, The University of Houston, December 5 and 6, 1973; Guest Speaker.

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"Concrete Shear Walls and Spandrel Beam Moment Frames Brace New York Office Tower," by Jay Ames, Joseph P. Colaco, Eli Dubinsky, Concrete International, June 1981.

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"What the Steel Designer Expects from the Fabricator," presented to AISC Operating Personnel meeting, Houston, May 24, 1984.

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"Preliminary Design of Low-Rise Office-Type Structures," November 13, 1985.

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"The Mile High Dream," Civil Engineering, April, 1986, page 76.

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"Haunched-Girder & Shear Wall Frames 42-Story Barnett Plaza in Tampa," Concrete International, November 1986, Vol. 8, No. 11, Page 35.

"Preliminary Design of Low Rise Buildings," Building Structural Design Handbook, edited by Richard N. White and Charles G. Salmon, John Wiley & Sons, 1987; Chapter 10.

"Structural Concepts for Ultra-Tall Concrete Buildings," IABSE Symposium Report, Paris-Versailles, 1987.

Presented "Caveats in A58.1-82 Provisions," to Session No. 2 of the Symposium on High Winds and Building Codes, NSF/WERC, Kansas City, Missouri, November 2, 1987 (published in proceedings).

"Tapered Drop Panel System," by Joseph P. Colaco and Javed B. Malik, Concrete International, September, 1988, Vol. 10, No. 9.

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Presented lecture "Barnett Plaza, Jacksonville," to ACI Chapter meeting, Jacksonville, Florida, October 19, 1989.

"Criss Cross Composite-Super Column Frames for 57-story NationsBank Plaza," Structural Steel Conference, by Joseph P. Colaco, P. V. Banavalkar, J. Malik, and A. Wahidi, Tokyo, Japan, October, 1992.

"Steel and Steel Composite Structures for High-Rise Buildings," Lehrstuhl and Institute für Massivbau, Aachen, Germany, March 31, 1994.

"Joint Design in Composite Columns/Steel Beam Structures" at Structures Congress, Irvine, California, April, 1993.

Lecture at International Workshop on "High Rise Buildings" at Delft University, the Netherlands, June, 1993.

"One Ninety One Peachtree and NationsBank - Composite Additions to the Atlanta Skyline" by P. V. Banavalkar and J. P. Colaco at the Structures Congress, Atlanta, Georgia, April, 1994.

"Two Prudential Formula – AE + LSH + CBM" by J.P. Colaco and A. Wahidi, Structural Design Codes and Special Building Project, Council of Tall Buildings and Urban Habitat 1997.

Practitioner Seminar Series, Korean Institute of Construction Technology, Seoul, Korea, April 22 & 23, 1998

Keynote Lecture at The 6th ASCCS International Conference, presented "Composite and Hybrid Construction in North America", Los Angeles, California, March 22, 2000.

The Concrete Industry's Strategic Development Council, "Concrete Technology Needs – The Architects & Engineers Speak", Houston, Texas, May 10, 2000.

"Complete Retrofit of a 47-story Steel Building for Wind Loads", by Joseph P. Colaco, Wally Ford, & Gene Robertson, Council of Tall Buildings & Urban Habitat Review/Volume 1 No. 1: pp. 30-37, May 2000.

"Design Office vs. Composite Construction", by Joseph P. Colaco & Ivan Viest, United Engineering Foundation, Inc., Composite Construction IV Conference, Banff, Alberta Canada, June 2, 2000.

"Concrete Buildings-A Mile High", by Joseph P. Colaco, 4th International Conference IFHS-International Federation of High-Rise Structures, Madrid, Spain, November 8, 2000.

Hi-Rise Composite Buildings by Joseph P. Colaco, Civil Engineering Department, University of Houston, January 31, 2001.

"Composite Buildings Systems", by Joseph P. Colaco, Civil Engineering Department, Texas A & M University, February 14, 2001.

"Natural Disasters – Rebuilding of Infrastructure", American Society of Indian Engineers – March 30, 2001.

"Latest Trends in Tall Composite & Concrete Buildings", University of Houston, Civil Engineering Dept., April 23, 2001.

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"Tall Building Design Developments", Houston HAER (Historic American Engineering Record) Exhibit Opening & Design Developments, July 12, 2001.

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"Safety Issues Related to Tall Buildings", The UH Forum: Imagining the World Beyond September 11*, November 6, 2001.

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"Prevention of Progressive Collapse", Multi-hazard Mitigation Council National Workshop, July 10-12, 2002.

"Affordable, Safe Housing Based on Expanded Polystyrene (EPS) Foam and A Cementitious Coating, October 8, 2003

"Design and Construction of an Innovative Panel System for Affordable, Safe, Energy Efficient Housing" The Academy of Medicine, Engineering and Science of Texas Conference, Houston, Texas, January 5-6, 2006.

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Contributed chapter entitled "Design of Tall Building" for book titled "Tall Buildings: Design Advances for Construction" edited by Dr. John Bull to be published by Civil-Coup Ltd using their imprint Saxe-Coburg Publications in the year 2006.

"Tall Residential Towers in Dubai – New Structural Systems" 4th International Specialty Conference on The Conceptual Approach to Structural Design, June 27 – 29, 2007 Venice, Italy Conference Speaker

"Innovative Concrete Concepts for Design and Construction of Buildings" – RAC07 – Recent Advances in Concrete Technology, September 19-21, 2007 Conference Speaker

CBM Engineers, Inc.
World Trade Center 7: Joseph Colaco Expert Report
Draft
February 15, 2010

1. Introduction

On September 11, 2001, World Trade Center 7 (WTC 7) collapsed from fires at 5:21PM, seven hours after the collapse of World Trade Center Buildings 1 and 2 at 9:59 and 10:28AM, respectively. Debris from the collapse of WTC 1 fell on the southwest corner and the south façade of WTC 7. WTC 7 was not hit by an airplane, was not doused with thousands of gallons of highly flammable jet fuel, and sustained only minimal local structural damage from the falling debris from WTC 1 and 2. Fires were ignited inside the southwestern quadrant of WTC 7 from the debris from WTC 1. These fires resulted in the collapse of WTC 7. WTC 7 became the first high rise steel building to ever suffer a global collapse from an office contents fire. In conjunction with GNA, a study was conducted to determine why this building became the first high rise steel building to ever suffer a global collapse from fire and whether this building could and should have been designed and constructed so as to have avoided this unique status.

> **As a result of this study, I have concluded that the design and construction of WTC 7 deviated from the standard of good engineering practice of world class engineers who design these type buildings and that these deviations were sufficiently serious to have caused the global collapse of WTC 7.**[1]

[1] This opinion and all other opinions stated in this report are expressed to a reasonable degree of scientific probability.

2. Qualification

A. Education

Dr. Joseph Colaco received his B.E. Civil, University of Bombay in 1960, M.S. (1962) and Ph.D. (1965) in structural engineering from the University of Illinois.

B. Experience

1965 – 1969	Skidmore, Owings and Merrill, Chicago
1969 – 1975	Ellisor Engineers, Houston
1975 – present	CBM Engineers, Houston

C. Notable Projects

(i) 100 story John Hancock Centre, Chicago.

On this project designed in 1965 – 1966, Dr. Colaco was responsible for the computer analysis of the exterior diagonally braced frame. Significant information:

- Factor of safety for exterior columns was 2.3.
- Double diagonal redundant system was used on the exterior diagonally braced frame
- A special disproportionate collapse analysis was done due to the on-going bombings of ROTC buildings in the USA during the Vietnam War.

(ii) 75 Story J. P. Morgan Chase (Texas Commerce) Tower, Houston

Dr. Colaco was in charge of the conceptual structural design. This is the tallest composite structure in the USA and was designed in 1978. The exterior columns and spandrels are composite and there is a composite shear wall in the core. The interior columns and floors are steel framed.

- All floor beams and girders are composite.

(iii) 64 Story Williams (Transco) Tower, Houston

Dr. Colaco was in charge of the conceptual structural design. This is a 64 story all steel tower that was designed in 1980. The structural system is a perimeter tube with columns at 15' on center. Interior gravity columns, floor beams, metal deck and lightweight concrete slab complete the assembly.

(iv) 60 Story Two Prudential Tower, Chicago.

This building was designed in 1987 and is one of the tallest (1000') all concrete buildings in the USA. Dr. Colaco was in charge of the conceptual design. Outrigger beams were placed at the 38th floor connecting the core shear walls to the exterior columns.

(v) 46 Story 101 Park Avenue, NY

This building designed in 1980, is an office building which started as an all steel building. It was changed to all concrete structure for economical reasons. Dr. Colaco was in charge of the conceptual design.

(vi) 42 Story Commerce Square, Philadelphia

This is a building designed in 1985. It has core bracing in two directions and an exterior welded frame. The floor framing was composite beams and girders, metal deck and composite slab. Dr. Colaco was in overall charge for the office.

D. Publications, Lectures, Committees and Teaching

COMMITTEE WORK

Board of Directors of Wind Engineers Research Council (WERC), 1990 - 1993

ASCE: Committee on Composite Construction, Chairman 1991 - 1994

ASCE: Committee on Wind Effects

ASCE: Task Committee on Structural Damping Systems

ACI: Committee on Mat Foundation, Committee 336

CONSTRUCTION INDUSTRY COUNCIL OF HOUSTON: Committee on Proposed Changes to the Houston Building Code; Member

ACADEMIC

Former Member of Advisory Council, Rice School of Architecture, Rice University

Former Board Member, Rice Design Alliance (1983 - 1989)

Former Member of Advisory Council, George R. Brown School of Engineering, Rice University, 1986 to 1998

1970/Present: University of Houston, Houston, Texas; lecturer/professor in the College of Architecture

1976/1997: Rice University, Houston, Texas; lecturer of Architecture on part-time basis

1968/1969: Illinois Institute of Technology, Chicago, Illinois; lecturer

1966/1968: University of Illinois, Chicago Circle Campus; lecturer

1962/1965: University of Illinois, Urbana, Illinois; research assistant

AWARDS

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Member, National Academy of Engineering, 1994

Distinguished Alumnus, Civil Engineering, University of Illinois

Distinguished Alumnus, College of Engineering, University of Illinois

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"Prediction of Steel Force Distribution in Reinforced Concrete Members from Bond/Slip Characteristics," PhD Dissertation, University of Illinois, 1965

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"End Moments for Floor Beams Framing into Spandrels," American Concrete Institute (ACI) Journal, January 1971.

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"A Stub-Girder System for Steel Floors in High-Rise Buildings," American Institute of Steel Construction (AISC), July 1972.

"Large Scale Concentration and Conversion of Solar Energy," by A. F. Hildebrant, G. M. Haas - Department of Physics, University of Houston; and by W. R. Jenkins, J. P. Colaco, College of Architecture, University of Houston, April 1972.

"Pennzoil Place - A New Slant in Structural Systems," by P. V. Banavalkar and J. P. Colaco; presented to ASCE-IABSE Regional Conference on Tall Buildings, Bangkok, Thailand, January, 1974 (published in the proceedings).

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"Affordable, Safe Housing Based on Expanded Polystyrene (EPS) Foam and A Cementitious Coating, October 8, 2003

The Structural Engineers Association of Texas, Technical Lecture "The History and Future or Tall Buildings by Joseph Colaco, PhD., P.E.", September 2004

"Design and Construction of an Innovative Panel System for Affordable, Safe, Energy Efficient Housing" The Academy of Medicine, Engineering and Science of Texas Conference, Houston, Texas, January 5-6, 2006.

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"Innovative Concrete Concepts for Design and Construction of Buildings" – RAC07 – Recent Advances in Concrete Technology, September 19-21, 2007 Conference Speaker"Tall Concrete Apartment Buildings and Composite Office Buildings" April 25 – 26, 2008

"Tall Concrete Apartment Buildings and Composite Office Buildings" April 25 – 26, 2008
JNTU College of Engineering, Kukatpally, Hyderabad, India, National Workshop on High Rise Buildings (NWHRB) Lecture XVII

ICI - Innovative World of Concrete 2008, Concrete For New Age Structures, New Delhi, India, Key Note Speaker – Lead Paper "Tall Concrete Residential Buildings and Composite Office Buildings"
Chair, Session No. 4 "Green Concepts and Environmental Impacts"

December 11 – 14, 2008
4th International Conference on "The Concrete Future" Recent Advances in Concrete Technology and Concrete in Structures, University of Coimbra, Polo II – Ilha de Marrocos, 3030-290 Coimbra, Portugal
June 17 – 19, 2009

The Structural Engineers Association of Texas, Technical Lecture "Philosophy of Structural Engineering for the Burj Dubai Tower" October 2009

E. List of Testimonies during the Previous 4 Years

2007 – Embassy Suites Lawsuit – RGM Constructors vs. Tribble and Stephens

2007 – Watersridge 3

2007 – Episcopal High School vs. Telepsen et. al.

F. Rate of Compensation

Principal Rate	$300.00 per hour
Principal Deposition and Testimony Rate	$400.00 per hour
Non-Principal Rate	2.5 times Direct Personnel Expense, which is 1.4 times Non-Principal Salary at the time service is performed.

3. Materials Reviewed

In preparation of the report, I have reviewed and analyzed numerous materials including the following:

Item	Additional Information	Author	Date
Structural Drawings	S1-S8,S12-25	Irwin Cantor and Associates	1985
Material Specifications (Section 05100 – Structural Steel)	Cantor Documents (CANTOR0008352 - CANTOR0008362)	Irwin Cantor and Associates	1981
Section 10B Specification Testing and Inspection WTC 7	Cantor Documents (CANTOR0006302 - CANTOR0006325)	Irwin Cantor and Associates	1981
Inspection Report (Steel Erection - Correcting Gaps of Column Splice by Fixing Shims in the Gap from 3rd to 11th Floors Respectively)	Cantor Documents (CANTOR0015827 - CANTOR0015843)	Irwin Cantor and Associates	11-12-1985
Truss 1 and 2 Collar Bracing Modification	Cantor Documents (CANTOR0011423 - CANTOR0011426)	Irwin Cantor and Associates	9-10-1985
Salomon Brothers Inc. Base Building Modifications 7 World Trade Center Structural Computations	Cantor Documents (CANTOR0020472 - CANTOR0020490)	Irwin Cantor and Associates	1-30-1989
Floor Vibration Calculation	Cantor Documents (CANTOR0002153 - CANTOR0002172)	Irwin Cantor and Associates	6-22-1984

Item	Additional Information	Author	Date
Typical Floor Calculations (Vol. 1)	Cantor Documents (CANTOR0004195-CANTOR0002082)	Irwin Cantor and Associates	1-15-1985
Computations for Transfer Trusses and Girders	Cantor Documents (CANTOR0003395-CANTOR0003515)	Irwin Cantor and Associates	1984
The Secret Service Agency Relocation of New York Field Office to 7 World Trade Center Tenant Floors 9 and 10 Structural Calculation	Cantor Documents (PANYNJ0095584 - PANYNJ0095866)	Irwin Cantor and Associates	8-26-1994
Architectural Drawings		Emery Roth and Sons PC Architects & S.O.M.	1985
Structural Shop Drawings	1-2000,3001-3141,4001 4501,9100-9202	Frankel Steel Limited	11-12-85
Field Work Drawings		Frankel Steel Limited	1985
Electrical, Mechanical and Plumbing Drawings		Various Companies	
Salomon Brothers Tenant Fit-Out and Alteration Architectural and Structural Drawings		S.O.M. & Irwin Cantor and Associates	
Metal Deck Shop Drawings		Nicolas J Bouras	
Floor Trench Shop Drawings		Mac Fab	
Specifications for Structural Steel, Concrete Slabs and Metal Decking		Port Authority of New York and New Jersey	
Laboratories Testing and Inspection Reports for Concrete, Welding, Spray-on Fire Protection, and Structural Steel Erection		Testwell Craig	
Mill Test Reports		US Steel Co, Stelco, Bethlehem Steel, Algoma, and British Steel Co	

Item	Additional Information	Author	Date
Miscellaneous Correspondences, Sketches, and Calculations		Various Companies	
Contractor Change Orders Related to Structural Steel, Shear Studs, Metal Deck, Concreting, Foundations and Fire Proofing		Various Companies	
Manual of Steel Construction	8th Edition	American Institute of Steel Construction (AISC)	1980
Steel Design Guide 19	Fire Resistance of Structural Steel Framing	American Institute of Steel Construction	2003
FEMA 356	Prestandard and Commentary for the Seismic Rehabilitation of Buildings	Federal Emergency Management Agency	November 2009
New York City Charter and Administrative Code Vol. 3-A	NYC Building Code	Edith L. Fisch	1978
A Study of Wind Effects for the No. 7 World Trade Center, New York, N.Y.	Wind Tunnel Study	N. Isyumov and M. Poole	9-83
Reference Standard 9	NYC Loading Standards		
ANSI Minimum Design Loads for Buildings and Other Structures	Progressive Collapse	American National Standard	1982
The BOCA Basic Building Code	Progressive Collapse	BOCA International	1975
Counter Terrorism Perspectives: The World Trade Center		Office for Special Planning Public Safety Department	1984
Defendant Citigroup Photographs	CITIWTC 7072468 - CITIWTC 7074277 CITIWTC 7096863 - CITIWTC 7096872		2-9-2007
Photo & Video Archive			
Deposition Transcripts and Exhibits of Irwin Cantor			1-27-2009 & 1-28-2009
Deposition Transcripts and Exhibits of Akbar Tamboli			4-2-2009

Item	Additional Information	Author	Date
Deposition Transcripts and Exhibits of Ramon Gilsanz			5-28-2009
Deposition Transcripts and Exhibits of Silvian Marcus			8-12-2009
Deposition Transcripts and Exhibits of John Salvarinas			10-7-2009
Deposition Transcripts and Exhibits of Jeffrey Smilow			10-22-2009

4. Description of Structural Frame

WTC 7 was a 47-story steel framed building. It had a number of unusual and challenging structural design features. First, WTC 7 was built on top and around an existing Con-Edison substation. The original foundation and support provided for a future office tower was not nearly sufficient for the structure which was actually built. Second, the building was trapezoidal in shape, to correspond with the congruent shape of the land upon which it was erected. Third, the existing sub-station prevented, in some cases, installation of columns which would transfer building loads directly to caissons below ground, necessitating multiple core load transfer structures in the form of three (3) massive two-story trusses. Fourth, the above-ground presence of the sub-station on the north side of WTC 7 required construction of cantilevered girders in order to increase the rentable space. Fifth, the Owner/Architect's requirement of large open floor bays on the north-east side of WTC 7 combined with the presence of an existing truck ramp allowing vehicular access to the WTC 7 garage resulted in columns on the northeast side of the building that had to support unusually large tributary areas. Lastly, given the desire to build a hi-tech building, multiple trench headers were required in the floor system, as shown in Figure 4.1. Despite their presence on most floors, these trench headers were not shown on the original structural drawings for floor above the 8th floor.

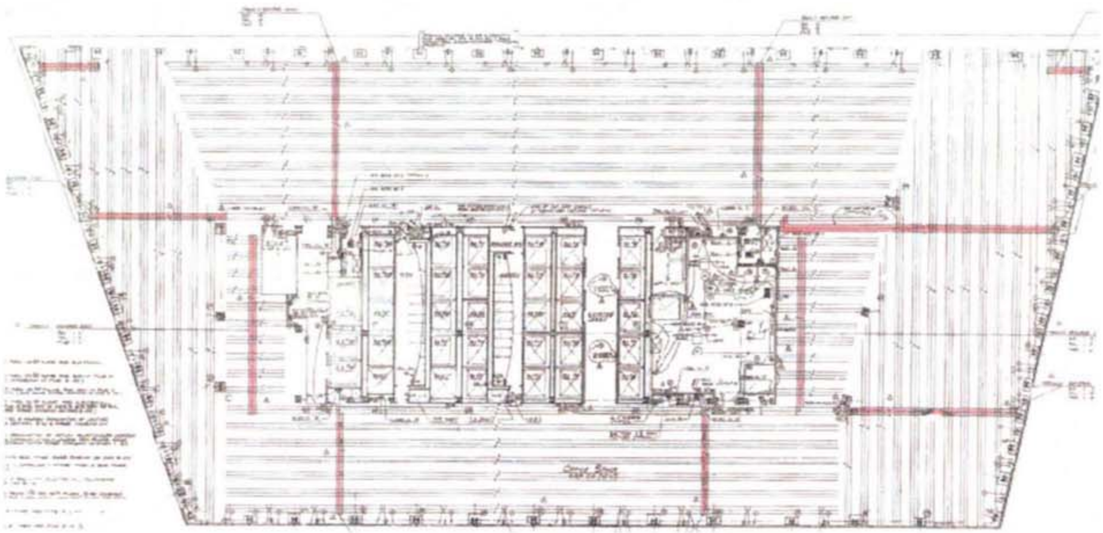

Figure 4.1 Location of Trench Header Ducts

The three transfer trusses, each located between the 5th and 7th floors were designed to carry and transfer the loads of the forty floors above them. Transfer trusses 1 and 2 were each comprised of two diagonals, which supported columns 76 and 77, respectively, neither of which continued to the ground level. Moreover, column 76 terminated at the 7th floor, on top of truss 2. Transfer truss 3 supported a hanging column 61A and consisted of two bays of diagonal members. The cantilevered girders located on the north face of WTC 7 on the 7th floor facilitated a setback of the exterior columns below the 5th floor so as not to encroach upon the existing Con Edison substation.

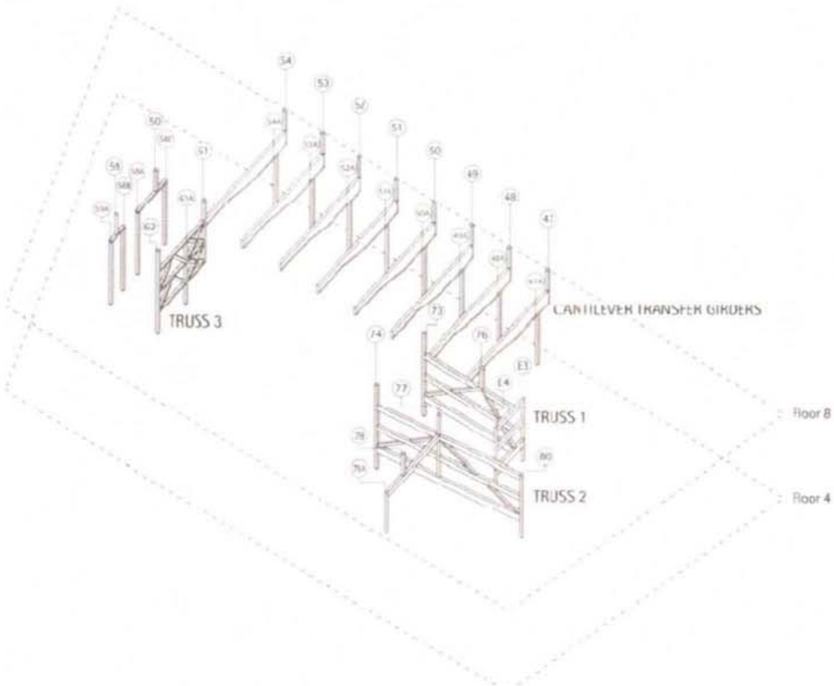

Figure 4.2 Transfer Trusses and Girders

With the exception of the fact that WTC 7 was erected atop and around a structure having a significantly smaller footprint, no single feature listed above would have been particularly unusual in high rise office buildings at the time. However, the aggregation of these elements exponentially increased the need for special attention to structural integrity, robustness and, among other things, connection details.

5. Serious Violations and/or Structural Problems with WTC 7

Numerous errors in the design and construction of WTC 7 reflect either inexperience, lack of understanding, inattention to important details, or simple carelessness. Whatever the cause, WTC 7 was not designed to a standard that would have been expected in an iconic structure in the World Trade Center in the 1980's. These failings are addressed below beginning with those that most likely contributed to the collapse of WTC 7 on September 11, 2001 and continuing with those that could have led to failures and disproportionate collapse in other initiating circumstances.

5.A Violation of 2% bracing (NYBC violation)

(i) Definition of Axial Bracing Requirement

It is common engineering knowledge that stability, robustness and structural integrity of a steel building require sufficient axial bracing (i.e. Section 5.31 in Steel Structures by William McGuire in 1968) for columns integral to the structure of the building. The New York City Building code specifies the minimum amount of such bracing. The New York City Charter and Administrative Code section C26-1001.2 states:

§C26-1001.2 Bracing – Unless otherwise specified in the reference standards, members used to brace compression members shall be proportioned to resist an axial load of at least 2 per cent of the total compression design stress in the member braced, plus any transverse shear therein.

Although written somewhat broadly, this code provision has been consistently interpreted by practicing structural engineers as requiring, at a minimum, that members along each axis provide an aggregate resistance of 2% of compressive design load to the compression members they brace. A typical bracing system of a compression member (such as a column) consists of beams or girders framing into it. For obvious reasons, these members cannot serve their critical function unless the connections attaching them to the columns are strong enough to allow load transfer. The 2% bracing requirement applies with respect to the members bracing the compression member as well as connections at such members. Thus, the ability of a member to provide axial bracing of 2% of the compressive design load alone is insufficient if the relevant connection cannot properly transmit such force.

Contrary to the view expressed by Mr. Smilow in his deposition (pages 152:23 - 153:9), unless specifically customized and detailed for direct bracing of the concrete to the column, the bracing system does not include concrete poured onto metal decking at each floor because (i) concrete poured around the weak axis of the column often does not contact the column surfaces, sometimes resulting in as much as a six-inch gap between the edge of the slab and the column, (ii) concrete poured around the strong axis of a column, although even if originally in full contact with the column, will often shrink away from it over time, preventing direct contact between the slab and the column and (iii) concrete poured around wet columns (such as column [**79**]) does not abut the column where pipes, conduits and risers vertically traverse from one floor to another. As such, the concrete does not develop sufficient composite action with the column to ever justify its inclusion into the axial bracing system required by the NYBC.

(ii) Axial bracing at Column 79.

Column 79 on typical floors is connected to three girders spanning between (i) column 44 and 79, (ii) column 76 and 79, (iii) column 80 and 79 (Fig 5.1)

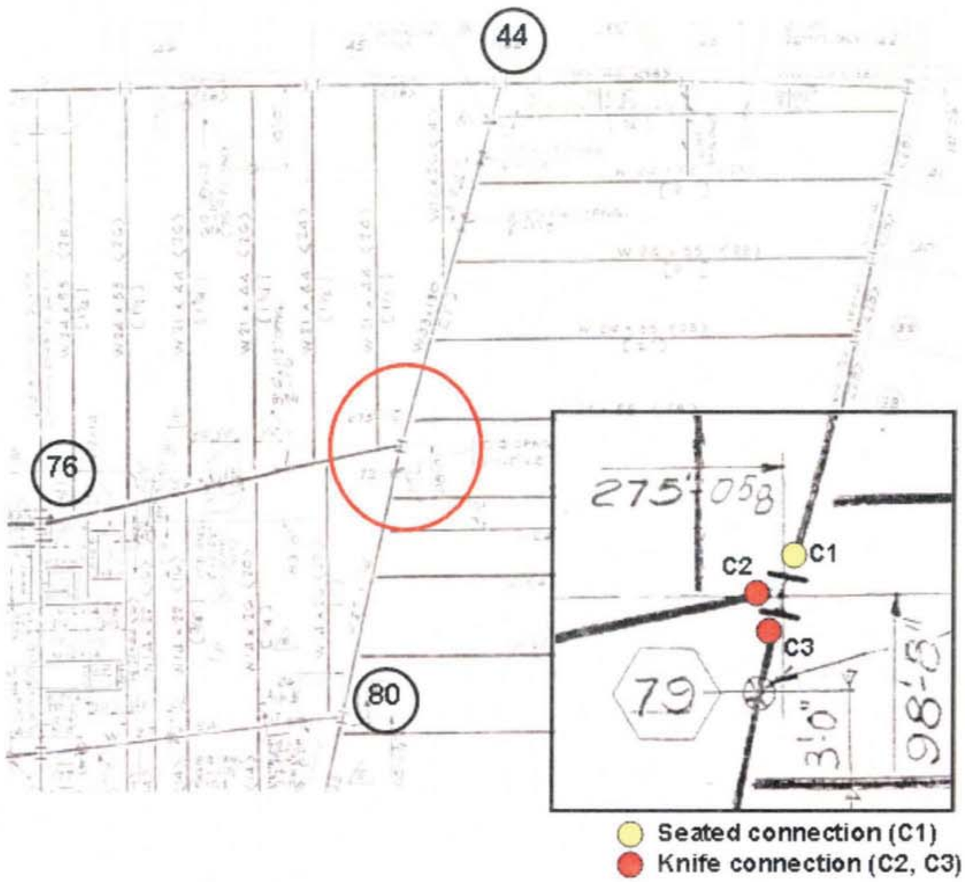

Figure 5.1 Types of Connections at Column 79

- **Types of Connections:**

There are three primary types of connections: (i) knife, (ii) header and (iii) seated. Those are shear connection types designed to transmit shear forces. The knife connection is made with two angles, one on each side of the web of a girder to be supported. The angles are bolted to a girder web and welded to a column flange. The header connection also consists of two angles but the difference from the knife connection is that the angles are welded to a girder web and bolted to a column web.

The seated connection transmits beam reaction through a seat that is welded to a column flange (Fig 5.2 to 5.4).

As seen in Fig 5.1, seated connection (C1) and two knife connections, (C2, C3) were used at column 79 on the most of the typical floors (floor 8 through 46). Figures 5.2 through 5.4 indicate the details of such connections. To prevent column 79 from buckling, the connections should have provided adequate lateral bracing in addition to transferring beam reactions to the column. It should be noted that column 79 had only 3-way bracing and no bracing from the east side to the weak axis of the column was provided. Only one skewed knife connection (C2) provides the lateral resistance against column buckling in east-west direction (weak axis of column 79), increasing the vulnerability of column 79.

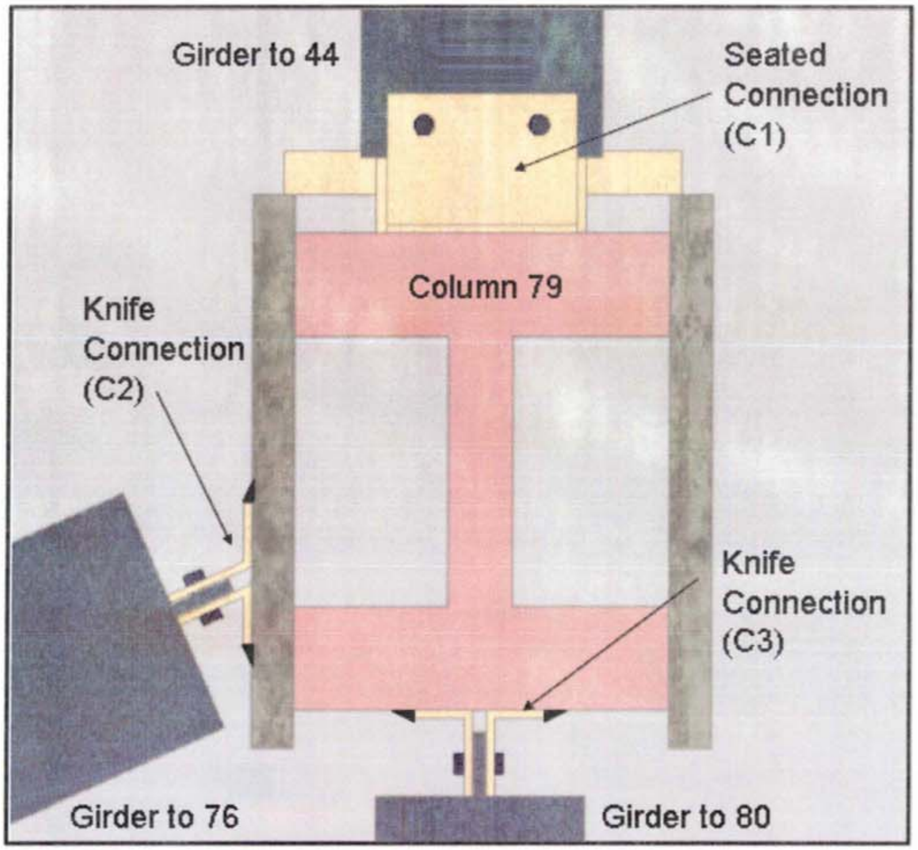

Figure 5.2 Plan View of Column 79 Connections

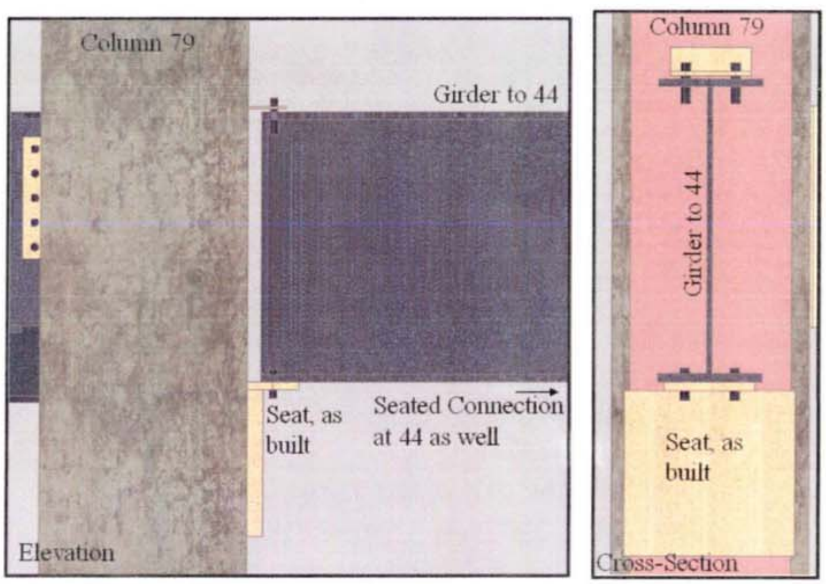

Figure 5.3 Elevation and Cross Sectional Views of Seated Connection (C1) at Column 79

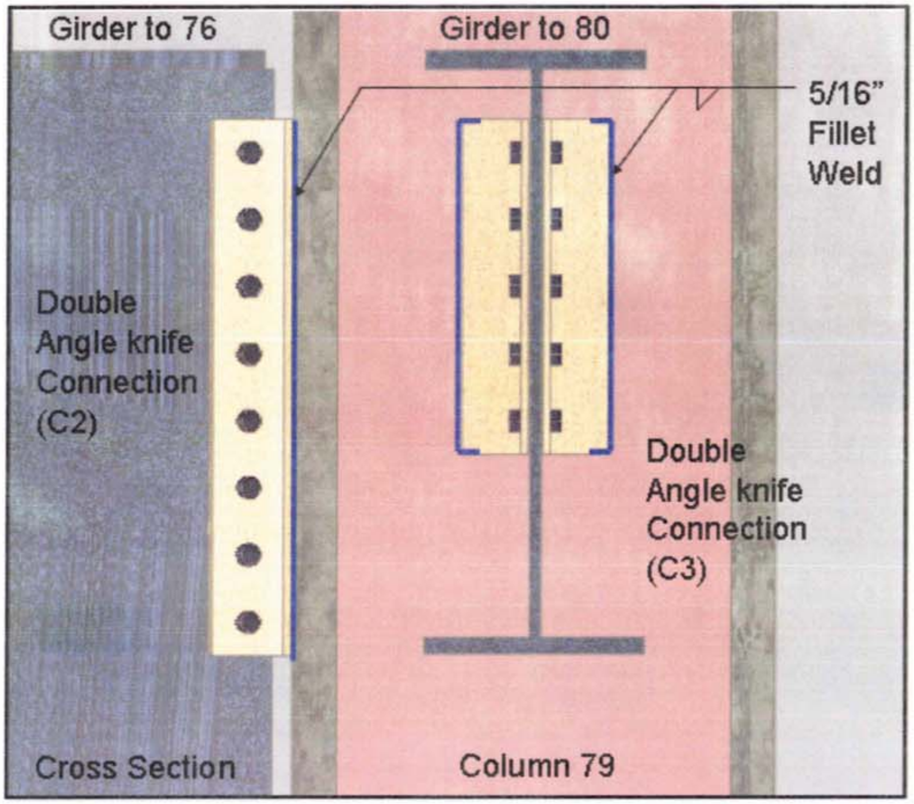

Figure 5.4 Cross Sectional View of Double Angle Knife Connection at Column 79

- **Bracing Capacity Provided by Connections**

  Connection capacities were calculated from the geometries provided in Frankel Steel shop drawings and the Manual of Steel Construction (8^{th} Ed.) published in 1980 by the American Institute of Steel Construction (AISC). Allowable Stress Design method (ASD) was used as a basis of the capacity calculations. The calculated capacities were compared with 2% of column axial loads shown on the structural drawings to verify whether the connections provided adequate bracing to columns.

  As shown in the figures above, only west side of column 79 is braced in the east – west direction. Therefore, the knife connection (C2) must provide enough bracing capacity both in tension and compression to meet the code requirement. In the north – south direction, column 79 has girder bracings in both directions (C1 and C3). When the seated connection (C1) is subjected to compression, the knife connection (C3) is simultaneously in tension or vice versa. Therefore, the connection bracing capacity should be the smaller value of compression capacity of C1 plus tension capacity of C3 or tension capacity of C1 plus compression capacity of C3.

- **Seated connection at 44-79 (C1 in Fig 5.1 & 5.2)**

This seated connection axial (compression and tension) capacity is controlled by bolt shear capacity.

For 7/8" Diameter A325 F-Type, shear capacity per bolt is:
10.5 kips (Single Shear Plane)
21.0 kips (Double Shear Plane)
(*Page 4-5 in AISC Manual 8th Edition*)

The girder top flange is connected to a clip angle with two bolts and the bottom flange is also connected using two bolts. Therefore, total four bolts are able to resist both axial compression and tension forces. Since each bolt has a single shear plane when it is subjected to axial forces, the total axial compression and tension capacity is:

$10.5 \times 4 = 42 kips$

- **Knife connection at 76-79 (C2 in Fig 5.1 & 5.2)**

The knife connection capacity in compression is controlled by bolt shear capacity. Since eight 7/8" Diameter A325 F-Type bolts have double shear planes when they are subjected to compressive forces, the compression capacity is:

$$21.0 \times 8 = 168 kips$$

When the beam is pulled away from the connection, due to their geometry and limits on weld locations, the angles of the connection deform (Fig. 5.5). The capacity of the double angles as a result of this behavior can be determined based on the principles of mechanics. Assuming that the angles are simply supported at the angle toes, critical section is approximately at "k" distance from the heel of the angle (Fig. 5.6). The k distance is defined as the distance from outer face of flange to web toe of fillet of rolled shape.

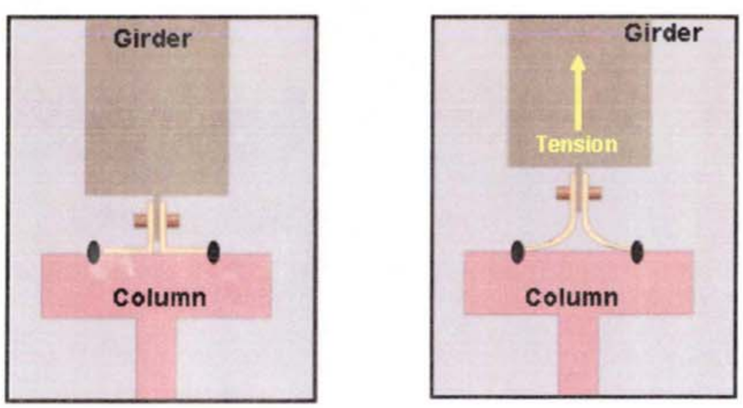

Figure 5.5 Plan View of Knife Connection Deformation in Tension

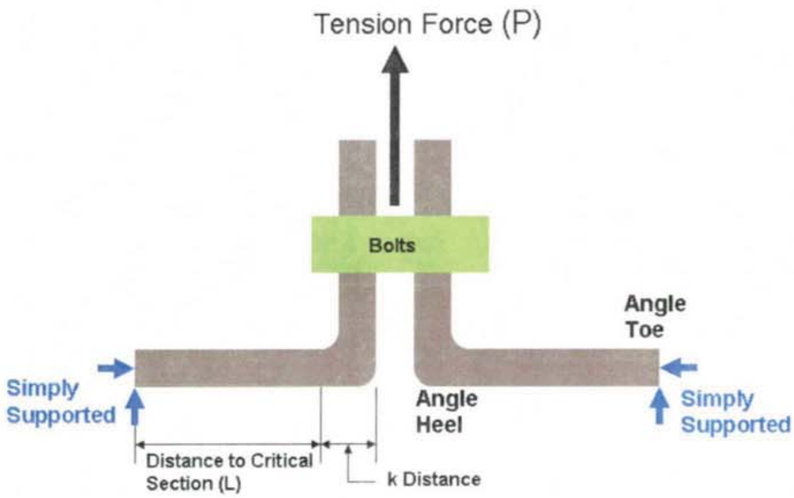

Figure 5.6 Free Body Diagram of Double Angle Connection in Tension

From a free body diagram of the angles, the elastic tension capacity of the connection (C2) can be calculated base on the following equations.

$$P \leq \frac{(0.75F_y \times S) \times 2}{L}$$

Where, Fy = Yield Strength of Steel (ksi)

S = Section Modulus of Leg of Angle (in^3)

L = Distance from Angle Toe to Critical Section (in)

P = Tension Force (kip)

For connection, C2

Fy = 44 ksi

Distance to Critical Section, L = 4" – 3/4" = 3.25 in

Section Modulus, S = 1/6 x $(3/8)^2$ x 24.5 = 0.574 in^3

Therefore, the maximum tension force P that the double angles can resist is 11.7 kips, which is significantly low capacity.

- **Knife connection at 79-80 (C3 in Fig 5.1 & 5.2)**

The connection toward column 80 is a double angle knife connection. The connection capacities in compression and tension can be calculated as discussed in the previous section.

The bolt shear capacity of five 7/8" Diameter A325 F-Type bolts with double shear planes is 21.0 x 5 = 105.0 kips. Therefore, the compression capacity of C3 is 105.0 kips

For the tension capacity of connection C3,

$$P \leq \frac{(0.75F_y \times S) \times 2}{L}$$

Fy = 44 ksi

Distance to Critical Section, L = 3" – 13/16" = 2.1875 in

Section Modulus, S = 1/6 x $(3/8)^2$ x 14.5 = 0.340 in^3

Therefore, the maximum tension force P that the double angles can resist is 10.3 kips.

- **Column 79 Connection Capacity Code Check Summary**

Based on the calculations above, bracing capacities provided by the connections were determined.

In the north – south direction, the provided connection axial capacity is: 42 kips (C1 compression capacity) + 10.3 kips (C3 tension capacity) = 52.3 kips. In the east – west direction, the axial connection capacity is 11.7 kips (C2 tension capacity)

It should be noted that the capacity calculations presented in the previous sections are based on the connections at floors 8 through 46. The connection capacities at the remaining floors and 2% of the column design loads are summarized in Table 5.1.

(1)	(2)	(3)	(4)	(5)
Level	Design Column Load [a] (kip)	Required Bracing Force (2%) [b] (kip)	Total North - South Connection Axial Capacity (kip)	Total East - West Connection Axial Capacity (kip)
Roof	198	4.0	214.4	32.0
47	494	9.9	52.3	28.4
46	790	15.8	52.3	11.7
45	978	19.6	52.3	11.7
44	1165	23.3	52.3	11.7
43	1352	27.0	No info	No info
42	1539	30.8	52.3	11.7
41	1726	34.5	No info	No info
40	1913	38.3	52.3	11.7
39	2100	42.0	52.3	11.7
38	2287	45.7	52.3	11.7
37	2474	49.5	52.3	11.7
36	2661	53.2	52.3	11.7
35	2848	57.0	52.3	11.7
34	3035	60.7	52.3	11.7
33	3222	64.4	52.3	11.7
32	3409	68.2	52.3	11.7
31	3598	72.0	52.3	11.7
30	3787	75.7	52.3	11.7
29	3972	79.4	52.3	11.7
28	4157	83.1	52.3	11.7
27	4344	86.9	52.3	11.7
26	4531	90.6	52.3	11.7
25	4718	94.4	52.3	11.7
24	4905	98.1	52.3	11.7
23	5141	102.8	52.3	11.7
22	5377	107.5	52.3	11.7
21	5589	111.8	52.3	11.7
20	5800	116.0	52.3	11.7
19	5987	119.7	52.3	11.7
18	6174	123.5	52.3	11.7
17	6361	127.2	52.3	11.7
16	6548	131.0	52.3	11.7
15	6735	134.7	52.3	11.7
14	6922	138.4	52.3	11.7
13	7109	142.2	52.3	11.7
12	7296	145.9	52.3	11.7
11	7483	149.7	52.3	11.7
10	7670	153.4	52.3	11.7
9	7857	157.1	52.3	11.7
8	8044	160.9	52.3	11.7
7	8278	165.6	194.8	8.1
6	8512	170.2	117.4	6.8
5	8813	176.3	261.1	12.9
4	9114	182.3	303.2	8.6
3	9345	186.9	164.5	8.5
2	9575	191.5	No info	No info

[a] Design Column Loads from Structural Drawings

[b] 0.02 x Col. (2)

Table 5.1 Column 79 Lateral Bracing Code Check (Connection Capacities in Red Indicate Code Violation)

(iii) Axial bracing at Column 80

- **Types of Connections:**

Column 80 on typical floors is connected to three girders spanning between (i) column 79 and 80, (ii) column 77 and 80, (iii) column 81 and 80 (Fig. 5.7) It is noted that the type of the connection toward column 77 (C5) is a seated connection only on the 8th and 9th floor and knife connections are used for the remaining typical floors. C5 is shown as a knife connection in Figure 5.7 and the knife connection axial capacity of C5 will be calculated in the following section.

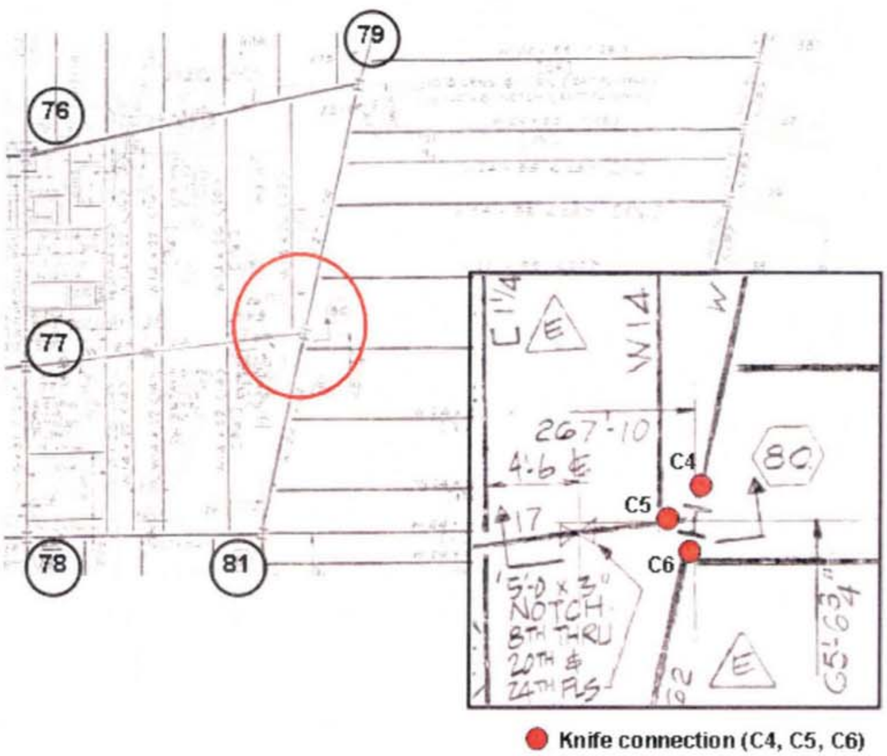

Figure 5.7 Types of Connections at Column 80

Similar to column 79, column 80 also has only 3-way bracing and no bracing from the east side of the column is provided. Only a skewed knife connection (C5) provides the lateral resistance against column buckling in east-west direction (weak axis of column 80), increasing the vulnerability of column 80. All three connections are similar to the double angle knife connection illustrated in the column 79 connection details (Figure 5.2 through 5.4)

- **Bracing capacity provided by connections**

Each connection axial capacity calculation and the comparison with the required capacity are discussed in the following sections

- **Knife connection at 79-80 & 80-81(C4 & C6 in Fig 5.7)**

The connections toward column 79 and 81 are double angle knife connections. The connection capacities in compression and tension are calculated as discussed in the previous section.

The knife connection capacity in compression is controlled by bolt shear capacity. The bolt shear capacity of five 7/8" Diameter A325 F-Type bolts with double shear planes is 21.0 x 5 = 105.0 kips. Therefore, the compression capacity of C4 and C6 is 105.0 kips

For the tension capacity of connection, C4 and C6

$$P \leq \frac{(0.75F_y \times S) \times 2}{L}$$

Fy = 44 ksi

Distance to Critical Section, L = 3" – 13/16" = 2.1875 in

Section Modulus, S = 1/6 x $(3/8)^2$ x 14.5 = 0.340 in^3

Therefore, the maximum tension force P that the double angles can resist is 10.3 kips.

- **Knife connection at 77-80 (C5 in Fig 5.7)**

Since six 7/8" Diameter A325 F-Type bolts have double shear planes when it is subjected to compressive forces, the compression capacity is:

$$21.0 \times 6 = 126 kips$$

For the tension capacity of connection, C5

$$P \leq \frac{(0.75F_y \times S) \times 2}{L}$$

Fy = 44 ksi

Distance to Critical Section, L = 3.5" – 13/16" = 2.6875 in

Section Modulus, S = 1/6 x $(3/8)^2$ x 18.5 = 0.434 in^3

Therefore, the maximum tension force P that the double angles can resist is 10.6 kips.

- **Column 80 Connection Capacity Code Check Summary**

  In the north – south direction, the provided connection axial capacity is: 105 kips (C4 compression capacity) + 10.3 kips (C6 tension capacity) = 115.3 kips

  In the east – west direction, the provided connection axial capacity is 10.6 kips (C5 tension capacity)

  It should be noted that the capacity calculations presented in the previous sections were based on the connections at the floors 10 through 47. The connection capacities at the remaining floors and 2% of the column design loads were summarized in Table 5.2.

(1) Level	(2) Design Column Load [a] (kip)	(3) Required Bracing Force (2%) [b] (kip)	(4) Total North - South Connection Axial Capacity (kip)	(5) Total East - West Connection Axial Capacity (kip)
Roof	198	4.0	115.3	18.5
47	494	9.9	115.3	10.6
46	790	15.8	115.3	10.6
45	978	19.6	115.3	10.6
44	1165	23.3	115.3	10.6
43	1352	27.0	No info	No info
42	1539	30.8	115.3	10.6
41	1726	34.5	No info	No info
40	1913	38.3	115.3	10.6
39	2100	42.0	115.3	10.6
38	2287	45.7	115.3	10.6
37	2474	49.5	115.3	10.6
36	2661	53.2	115.3	10.6
35	2848	57.0	115.3	10.6
34	3035	60.7	115.3	10.6
33	3222	64.4	115.3	10.6
32	3409	68.2	115.3	10.6
31	3598	72.0	115.3	10.6
30	3787	75.7	115.3	10.6
29	3972	79.4	115.3	10.6
28	4157	83.1	115.3	10.6
27	4344	86.9	115.3	10.6
26	4531	90.6	115.3	10.6
25	4718	94.4	115.3	10.6
24	4905	98.1	115.3	10.6
23	5141	102.8	115.3	10.6
22	5377	107.5	115.3	10.6
21	5589	111.8	115.3	10.6
20	5800	116.0	115.3	10.6
19	5987	119.7	115.3	10.6
18	6174	123.5	115.3	10.6
17	6361	127.2	115.3	10.6
16	6548	131.0	115.3	10.6
15	6735	134.7	115.3	10.6
14	6922	138.4	115.3	10.6
13	7109	142.2	115.3	10.6
12	7296	145.9	115.3	10.6
11	7483	149.7	115.3	10.6
10	7670	153.4	115.3	10.6
9	7857	157.1	115.3	42.0
8	8044	160.9	115.3	42.0
7	8278	165.6	180.6	12.1
6	8512	170.2	10.3	3.2
5	8813	176.3	274.2	N/A
4	9114	182.3	N/A	237.8
3	9345	186.9	187.7	6.4
2	9575	191.5	No info	No info

[a] Design Column Loads from Structural Drawings

[b] 0.02 x Col. (2)

Table 5.2 Column 80 Lateral Bracing Code Check (Connection Capacities in Red Indicate Code Violation)

(iv) Conclusion

WTC 7 failed to meet the 2% axial bracing requirement mandated by NYBC at each of Columns 79 and 80. Other interior columns (59, 60, 64, 66, 67, 69, 70, 72, 73, 75) are also found to be highly vulnerable by inspection due to the 3-way bracings with the knife type connections that provide insufficient bracing when subjected to tension. Given the trapezoidal shape of the building resulting in eccentric and skewed connections combined with oversized floor bays, double angle connections were not the correct type to provide lateral bracing of columns. They were incapable of transmitting the required 2% axial force at columns 79 and 80, leaving those columns vulnerable to buckling.

(v) Modification Required to Meet Code

This section shows a proposed alternate connection at column 79 to improve the bracing capacities and to satisfy the NYC Building Code requirement. As discussed above, the knife connections provide insufficient bracing capacity in tension due to the flexibility of the angles. In the alternate to meet the code, the double angles should have been changed to two shear tabs with the same number of bolts and similar size. For the seated connection (C1), it is proposed to use two shear tabs, (2PL4x$^3/_8$x2'-0$^1/_2$) with 8 bolts in order to increase the axial capacity of the connection. One side of the shear tabs is shop welded while the other side needs to be field welded for better constructability. The skewed connection towards column 76 (C2) is made of two plates a 4$^1/_{16}$x$^3/_8$x2'-5$^1/_2$" and a 4$^7/_{16}$x$^3/_8$x2'-5$^1/_2$" with 10 bolts. Towards column 80 (C3), the angles are changed to 2PL4x$^3/_8$x1'-2$^1/_2$ with 5 bolts (Figure 5.8 - 5.10)

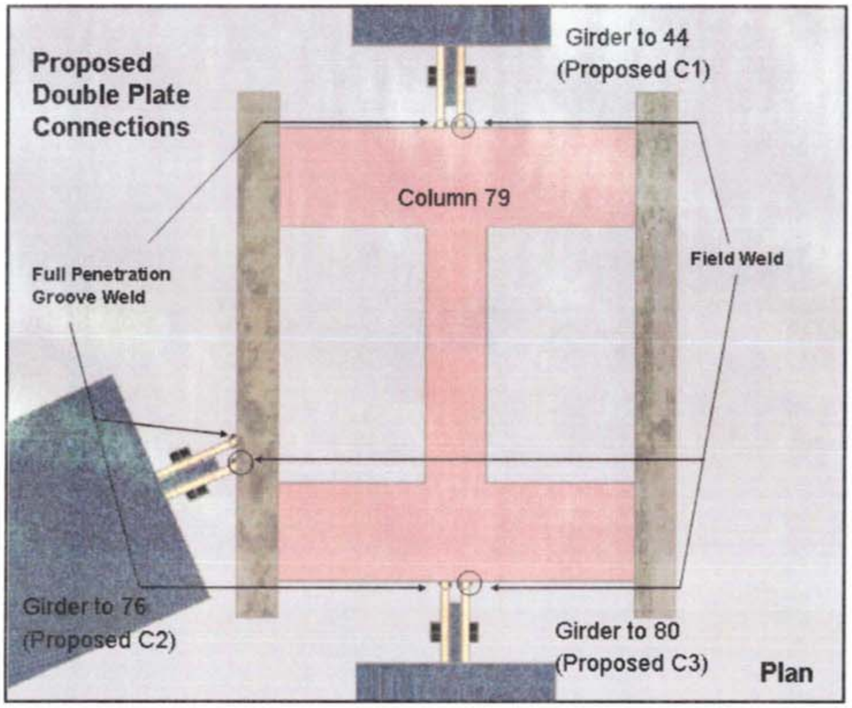

Figure 5.8 Plan View of Proposed Connections at Column 79 to Meet 2% Axial Bracing Force Requirement.

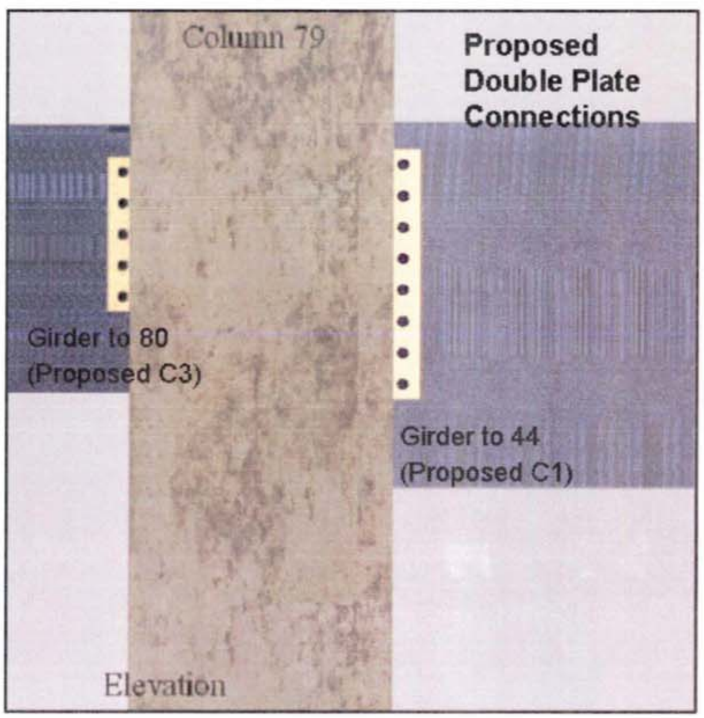

Figure 5.9 Elevation and Cross-sectional Views of Proposed Connections

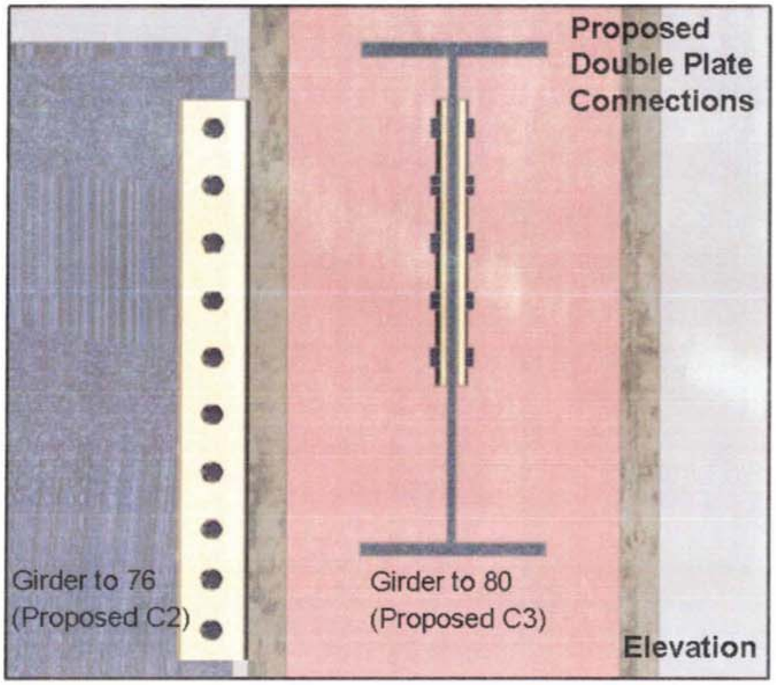

Figure 5.10 Cross-sectional View of Proposed Connections at Column 79

Installing the double shear tabs in lieu of double angles eliminates the prying effect in tension, which is the controlling failure mechanism of the as-built double angle connections when subjected in tensile forces. This proposed connection type significantly improves the bracing capacities in tension by directly transmitting axial forces through full penetration butt welds with no eccentricity. This proposed alternative connection is applicable to other vulnerable columns with double angle knife connections requiring negligible additional installation cost and time. The axial capacities of the proposed connections are summarized in Table 5.3 and corresponding calculations are shown below. As evidenced from the table, they meet the 2% axial bracing requirement of NYC Building Code.

Floor	Column	Connection Label	As Built Connection	Proposed Connection	2% Required Axial Capacity	Total Capacity of		Total Capacity of	
						North - South	East - West	North - South	East - West
8	79	C1	Seated with 4 Bolts	2PL4x3/8x2'-0 1/2" with 8 bolts	161	52.3	11.7	**171**	**184**
8	79	C2	Double Angle with 8 Bolts	PL4 1/16x3/8x2'-5 1/2" and PL4 7/16x3/8x2'-5 1/2" with 10 bolts					
8	79	C3	Double Angle with 5 Bolts	2PL4x3/8x1'-2 1/2" with 5 bolts					

Table 5.3: Summary of Connection Capacities vs. 2% Required

Proposed Connection Axial Capacity Verification

Column 79 Load at 8th Floor: 8044 kips

2% Required Axial Capacity: $8044 \times 0.02 = 160.9\ kip$

Col. 79 Proposed Connection towards Col. 44 (C1) Capacity

- Use two PL4x$^3/_8$x2'-0$^1/_2$" with 8 bolts

Bolt Shear Capacity

$21.0 \times 8 = 168\,kips$

Resultant Compression or Tension Capacity

(Subtracting Shear from Capacity)

$\sqrt{168^2 - 146^2} = 83.1\,kips$

Col. 79 Proposed Connection towards Col. 76 (C2) Capacity

- Use PL4$^1/_{16}$x$^3/_8$x2'-5$^1/_2$" and a PL4$^7/_{16}$x$^3/_8$x2'-5$^1/_2$" with 10 bolts

Bolt Shear Capacity

$21.0 \times 10 = 210\,kips$

Resultant Compression or Tension Capacity

(Subtracting Shear from Capacity)

$\sqrt{210^2 - 102^2} = 183.6\,kips$

Col. 79 Proposed Connection towards Col. 80 (C3) Capacity

-Use 2PL4x$^{3}/_{8}$x1'-2$^{1}/_{2}$ with 5 bolts

Bolt Shear Capacity

$21.0 \times 5 = 105\,kips$

Resultant Compression or Tension Capacity

(Subtracting Shear from Capacity)

$\sqrt{105^2 - 58^2} = 87.5\,kips$

Based on the calculations above, the provided connection axial capacity in the north – south direction is:

83.1 kips (C1 compression capacity) + 87.5 kips (C3 tension capacity)

= 170.6 kips > 153.4 kips

[MEETS THE NYBC 2% BRACING REQUIREMENT]

In the east – west direction, the provided connection axial capacity is:

183.6 kips (C2 tension or compression capacity) > 153.4 kips

[MEETS THE NYBC 2% BRACING REQUIREMENT]

5.B Resistance to Disproportionate Collapse.

(i) Definition of Disproportionate Collapse

Disproportionate collapse is the spread of an initial local failure from element to element, eventually resulting in the collapse of an entire structure or a disproportionately large part of it. Resistance to disproportionate collapse is often referred to as "structural integrity" as in American National Standards Institute ("ANSI") A58.1 -1982:

> "…buildings and structural systems shall possess general structural integrity, which is the quality of being able to sustain local damage with the structure as a whole remaining stable and not being damaged to an extent disproportionate to the original damage."

(ii) Industry Standard

Beginning, at least, with the disproportionate collapse at Ronan Point, England in 1968, structural engineers had been aware of, and concerned with, the dangers of disproportionate collapse from an initial failure. In 1972, ANSI A58.1 provided:

> "Progressive Collapse. Buildings and structural systems shall provide such structural integrity that the hazards associated with progressive collapse, such as that due to local failure caused by severe overloads or abnormal loads not specifically covered here in, are reduced to a level consistent with good engineering practice.[2]

---

[2] This precise language was contained in sec. 701.2 of the BOCA Basic Building Code (1975) as part of Sec, 701 entitled – "Design Safe Load". BOCA was the building code for New Jersey at the time and Cantor was familiar with it from other projects. (Cantor dep., pg. 326). Even more significantly, the Port Authority as a bi-state agency of both New York and New Jersey was intimately familiar with the fact that this BOCA requirement was a minimum standard for its buildings erected in New Jersey.

Although the New York City Building Code did not contain a specific provision mandating that buildings be designed to resist disproportionate collapse, a building that was not designed to meet the definition of structural integrity contained in the above paragraph, even before 1982, was not designed to a level consistent with good engineering practice, whether that building was built in New York City, New Jersey or anywhere else in the world. The New York City Building Code, like all local building codes, establishes only minimum requirements (NYBC C26-1000.1). Blind adherence to building code requirements is not the standard for good engineering practice. It is therefore surprising, and a major deviation from the standard of engineering practice in the 1980s, that the Office of Irwin Cantor gave no consideration to designing WTC 7, a high-rise, iconic structure with numerous structural engineering challenges, for resistance to disproportionate collapse because it was not explicitly required to do so by the NYCBC, as he testified at his deposition at page 353:3-12.

The wave of bombings of banks and other financial institutions in New York City in 1982 should have elevated resistance to disproportionate collapse to the forefront of the designer's mind in designing a new high rise steel office building in the financial district at that time. As far back as 1966, during the time of the Vietnam war and the bombings of ROTC buildings, I was working at Skidmore, Owings and Merrill on the design of the 100-story John Hancock Centre in Chicago, and performed a disproportionate collapse study on the design of the tower.

(ii) ANSI/ASCE

As indicated in the portion of this report defining "disproportionate collapse, 1982 ANSI § A58.1 publication American National Standard: Minimum Design Loads For Buildings And Other Structures explicitly required that consideration be given to the "structural integrity" of a building. Specifically, Section 1.3, entitled "General Structural Integrity", provided:

> Through accident or misuse, structures capable of supporting safely all conventional design loads may suffer local damage, that is, the loss of load resistance in an element or small portion of the structure. In recognition of this, buildings and structural systems shall possess general structural integrity, which is the quality of being able to sustain local damage with the structure as a whole remaining stable and not being damaged to an extent disproportionate to the local damage. ANSI § A58.1 (emphasis added).

As its name implies, ANSI has always provided the national standard for structural engineers in designing buildings. Failure to comply with the above standard in the design of WTC 7 was, by definition, a violation of the standard applicable to the industry in 1982.

(iii) Conclusion re: WTC 7 Design

Since the structural engineer admitted that he did not design WTC 7 to be resistant to disproportionate collapse, it is not surprising that the building was inadequately designed in the following ways:

(a) The Engineer of Record failed to specify axial force requirements for each beam-to-column connection on structural drawings supplied to the fabricator resulting in (i) almost half of the floor-to-interior column joints in the building not meeting even the minimum lateral bracing code requirement in at least one direction and (ii) 75% of the interior columns having at least one lateral bracing code violation.

(b) The unwarranted delegation of design/detail responsibility for critical connections like Column 79 and 80 to the fabricator and failure to adequately supervise the fabricator led to improper design of connections and their subsequent inability to transmit the required axial forces. A mere review of the three-sided connection at Columns 79 and 80 would have alerted the Engineer of Record to the impossibility of designing an adequate double angle "knife" connection.

(c) Good engineering practice requires that each exterior column should have 3 girders framing into it and each interior column should have 4 girders framing into it. However interior columns 59, 60, 64, 66, 67, 69, 70, 72, 73, 75, 79 and 80 only had girders only on 3 sides. Thus, an unpaired connection in the direction of the single girder had to provide the entire 2% bracing force. Therefore, most of the interior columns mentioned above failed the 2% axial bracing requirement. Four-sided bracing was particularly important for columns with large tributary areas like Columns 79 and 80, which should have been braced on 4 sides so as to prevent buckling in the event of a weakness of the unpaired connection.

Further, where possible, the 2% bracing should have been allocated equally among the 2 members bracing each side of the axis (i.e., 1% each).

(d) Columns 79, 80 and 81 had very large tributary floor areas. Hence any failure of the column or connections has a disproportionately large floor area impacted.

(e) Conventional knowledge indicates that for a 47 story building the economical structural system is a braced core with a perimeter welded frame going all the way up and down the building. Unfortunately the core bracing was stopped at the 7th floor. If the bracing was continued over the height of the building it would have helped to brace the interior core columns.

(f) Critical members such as transfer truss members, cantilever transfer girders etc. were designed with low factors of safety and no consideration for the critical nature of these members.

(g) Transfer Trusses 1 and 2 had three major design deficiencies.

> (i) *Lack of Redundancy*: The use of single diagonals creates the potential problem of disproportionate collapse due to failure of the diagonal or its connection. Double diagonals should have been used.
>
> (ii) *Factor of Safety*: A review of the calculations indicates that usual AISC factor of safety (1.6 to 1.9) were used as seen in Figures 5.11 and 5.12.

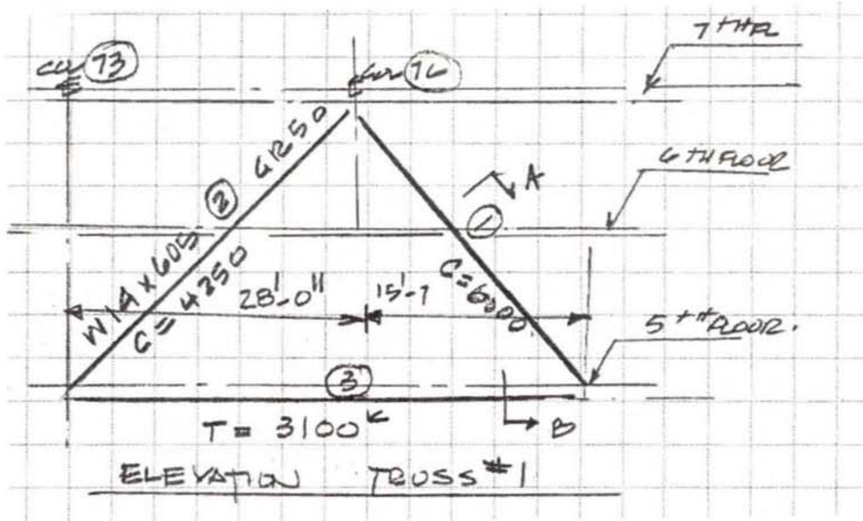

Figure 5.11 Excerpt from CANTOR200327 Showing Truss 1 Diagram for Calculations

(1) Memb. ① cont.

$L_{UUB} = (15.6^2 + 26^2)^{1/2} \div 2 = 15.17'$

$KL/r_{MIN} = 1.0(15.17)(12) / 4.55 = 40$

$r_{MIN} = \sqrt{I_Y/A} = \sqrt{4786/231} = 4.55$

Stresses

$f_a = 6000/231 = 25.9 \approx$ ok

$F_a =$ (based on $Kl/r = 4.55$) $= 25.83$ ksi.

% off = 0.5%

Figure 5.12 Excerpt from CANTOR200328 Showing Diagonal Design Calculations

In my opinion, transfer trusses should have been designed for higher than usual factors of safety due to the critical nature of the truss. For example the transfer girder at the Brunswick Building in Chicago, designed in the 1960's had a factor of safety of 3.0 (see Fig. 5.13).

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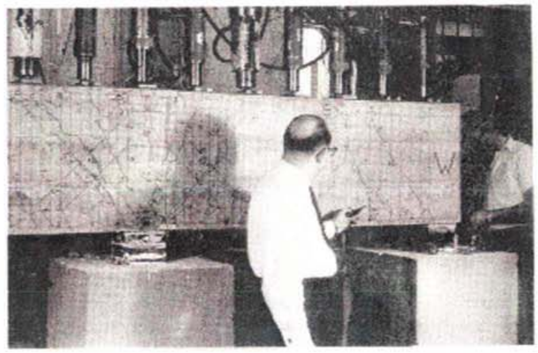
Brunswick Building, completed in 1965. The Chicago Civic Center Plaza is seen in the foreground. (Photograph by Hedrich-Blessing, courtesy of Skidmore, Owings & Merrill LLP)



Transfer girder investigation at the University of Illinois, 1962. (Photograph by Fazlur Khan.)

To study the behavior of the proposed transfer girders, the professors recommended the Structural Research Laboratory at the University of Illinois for model load testing, and Khan immediately contacted Chester Siess. A deep-beam research project interested Siess and fit into the scope of the lab's testing program, so the university agreed to undertake load tests for SOM's design. The subsequent laboratory tests confirmed the validity of Khan's design scheme for the transfer girder: based on twelfth-scale model tests of a two-span continuous beam, a safety factor on the order of 3.0 was predicted, yielding was shown to be in flexure, there was no apparent distress due to shear, and there was minimal effect of the horizontal construction joints. The tests also indicated that normal placement of primary reinforcement at the top and bottom of the beam, with secondary reinforcing at mid-depth, was appropriate—necessary confirmation, since ACI 318-56, "Building Code Requirements for Reinforced Concrete," did not cover deep beam design.[20]

Khan and Fintel monitored the structural behavior of the transfer girders and their 7-foot-square supporting columns during construction. Readings from gages installed in the structure verified their integrity and provided data for correlating analytical methods and observed structural behavior.

Figure 5.13 Excerpt from Engineering Architecture by Yasmin Sabina Khan (2004)

(iii) *Detail of Diagonal to Girder Connection*: A highly unusual and dangerous "collar" connection detail was originally designed as shown in Fig. 5.14. The floor beam was deliberately moved off the centerline of the diagonal which defies basic engineering principles. This detail inherently assumes that the diagonal will move sideways before the vertical plate on the girder will restrain further movement. No dimensions were provided on the maximum movement tolerated, construction tolerances, etc. Our analysis indicates that this detail would not have worked. This crucial detail was changed in the shop drawings process to the detail shown in Fig. 5.15. This new detail, though somewhat better, still contained most of the problems of the original "collar" design. .

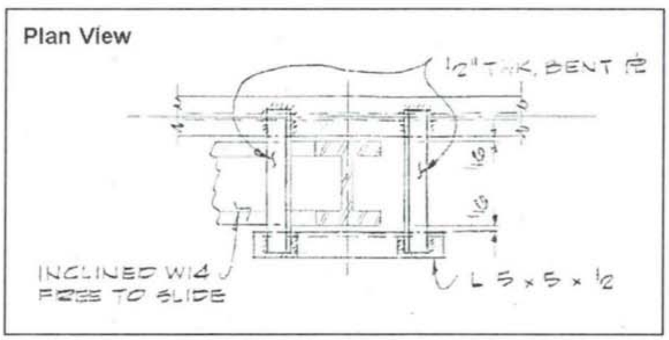


Figure 5.14 Original Collar Detail Shown on Cantor Structural Drawing (S-23)

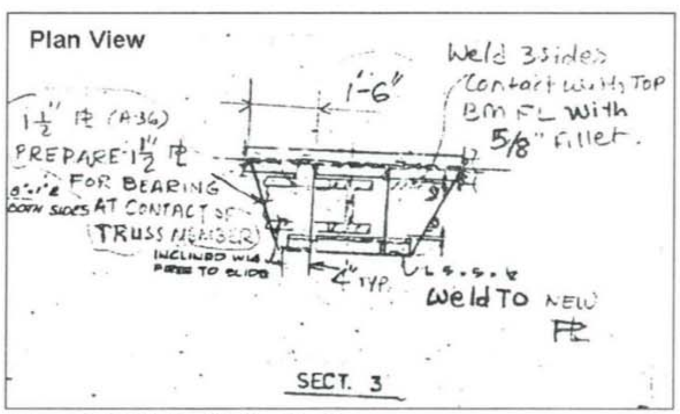


Figure 5.15 Revised Collar Detail

> In my opinion, a more rigid connection that is normally used should have been designed and fully detailed on the original drawings.

(h) There was no analysis conducted to see how the building would react if one of the important transfer system members were to fail. Had an "elimination analysis" been conducted with respect to transfer trusses and cantilevered transfer girds at WTC 7, such analysis would have clearly shown the building's susceptibility to disproportionate collapse. The transfer trusses had only single diagonal members (no double diagonals). Hence the failure of a diagonal or connection would be catastrophic. There was no consideration for redundancy or alternate load path which would have provided resistance to disproportionate collapse. Redundancy in the transfer trusses should have been created in the design to prevent a global collapse and make the building more robust. An additional truss could have been designed going south from Column 47A and connecting to Column 78A. This would ensure that if there was any problem with Trusses 1 or 2 that there was an alternate load path for the transfer columns 76 and 77. (See Figs. 5.16 and 5.17).

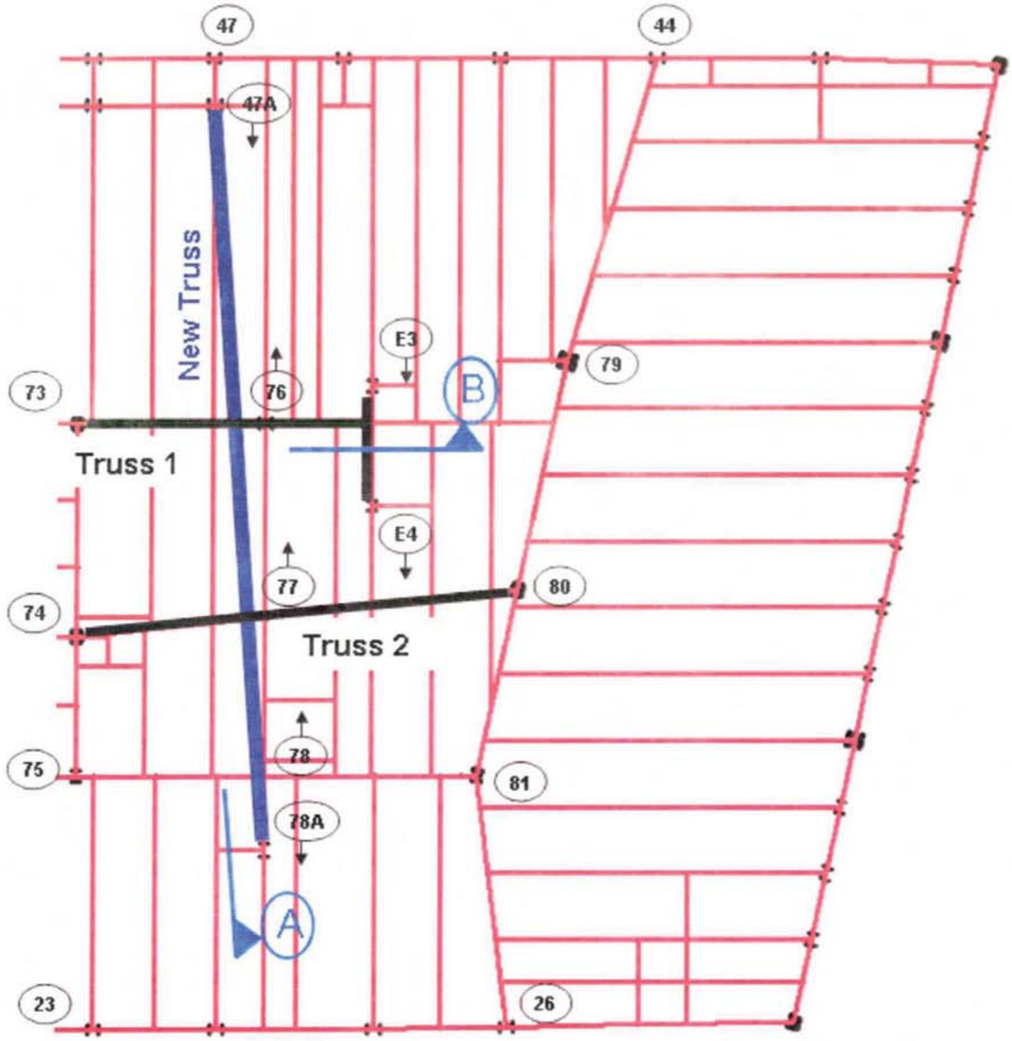


Figure 5.16 Location of proposed transfer truss on the 7th floor for an alternate design

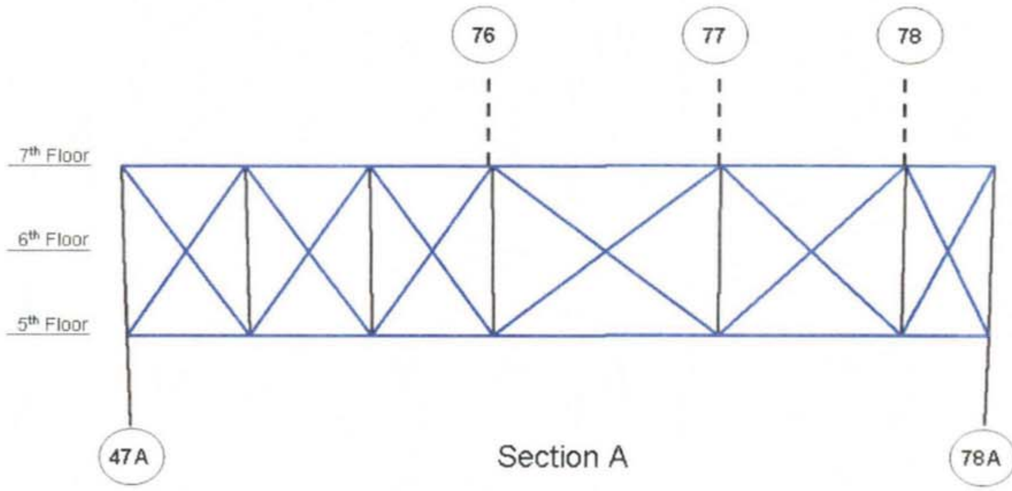


Figure 5.17 Elevation of proposed truss (Section A) as seen in Figure 5.16

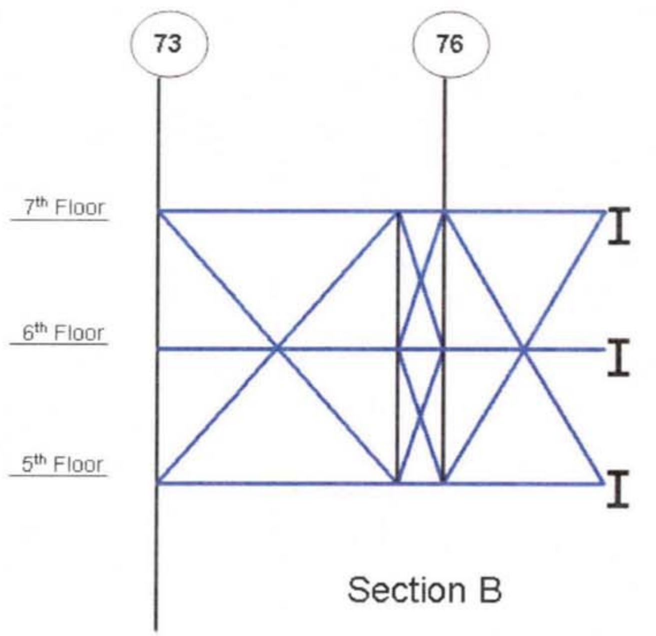


Figure 5.18 Elevation of proposed truss1 (Section B) as seen in Figure 5.16

(i) A designer and developer of any structure in 1982 should have been concerned with that structure's potential for disproportionate collapse. That requirement should have been even more obvious to the designer and developer of a building to be constructed in the World Trade Center Complex. No qualified engineer and developer should have designed and constructed a building with the multiple structural challenges presented by WTC 7, as set forth in Section 5.A(v) above, without designing and constructing it with sufficient structural integrity to resist disproportionate collapse as required by the standard set down in ANSI Sec. 58A.1 (1982).

(j) Both the core girders and other floor girders should have been designed fully composite. This would have given better behavior for floor deflection, floor vibration, column bracing and for fire resistance. Instead, critical girders in WTC 7 were made only negligibly composite at the construction stage through addition of a small number of sheer studs, solely to accommodate additional vertical load. Rather, all floor framing should have been designed as composite to provide sufficient connection between the floor slab and the framing to facilitate adequate transfer of lateral loads. This would have provided better structural integrity in general, including better bracing of interior columns and control of floor deflections and floor vibrations.

5.C Secondary Stresses (NYBC violation)

According to § C26-1001.3 of the New York City Charter and Administrative Code from 1978 (Fig 5.19):

§ C26–1001.3 **Secondary stresses.**—Secondary stresses in trusses shall be considered and where of significant magnitude, their effects shall be provided for in the design.

Figure 5.19 Page 305 of the New York City Charter and Administrative Code showing that secondary stresses must be checked.

To see if this had been followed, the stresses in the ETABS model under design loads were examined. They were checked at the top, middle and bottom of each truss diagonal in Truss 1 & 2. The diagonals were treated as elements with pinned connections (Fig 5.20 and Fig 5.21) and then elements with fixed connections (Fig 5.22 and Fig 5.23) since the actual case is in between. This was confirmed by a review of the shop drawing details of the connections showing a high degree of fixities at the joints.

(i) Pinned End Connections Study

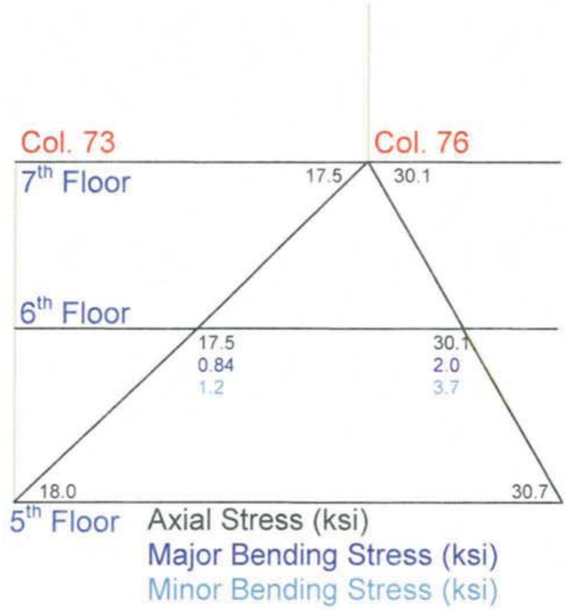


Figure 5.20 Stresses in Truss 1 diagonals taking the diagonals as having pinned connections at the top and bottom.

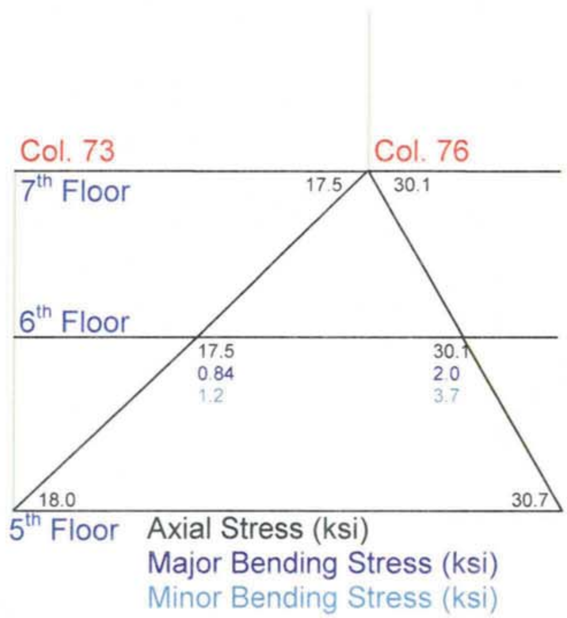


Figure 5.21 Stresses in Truss 2 diagonals taking the diagonals as having pinned connections at the top and bottom.

(ii) Fixed End Connections Study

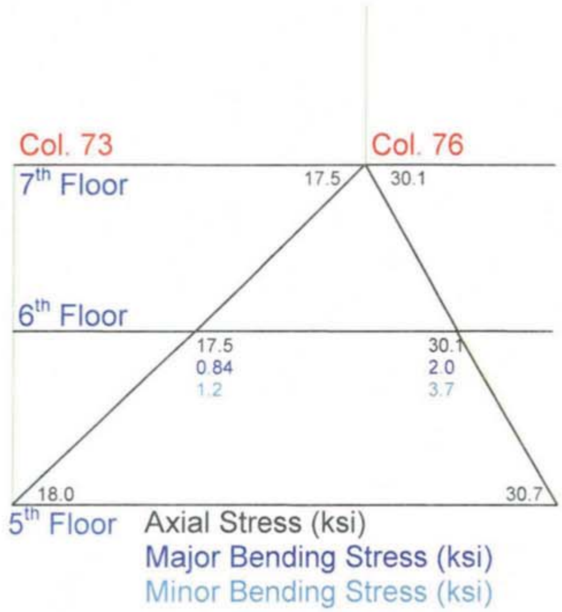


Figure 5.22 Stresses in Truss 1 diagonals taking the diagonals as having fixed connections at the top and bottom.

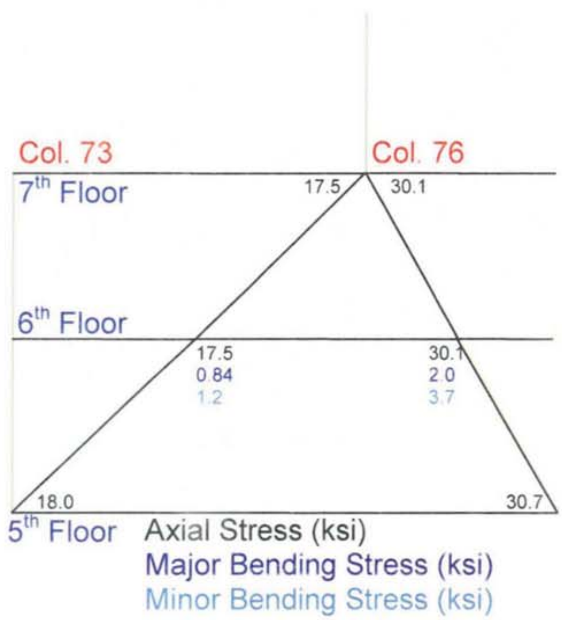


Figure 5.23 Stresses in Truss 2 diagonals taking the diagonals as having fixed connections at the top and bottom.

(iii) Conclusion

The secondary stresses are clearly of significant magnitude. Considering Truss 1, the sum of the secondary stresses is between 6.1 and 7.7 ksi at the middle of the right diagonal which is between 21% and 27% of the axial stress of 28.6 ksi. For Truss 2, the sum of the largest secondary stresses is between 0 and 8.1 ksi at the top left connection or between 0 and 35% of the axial stress of 23.3 ksi. Accordingly, these secondary stresses should have been considered in the design process. It appears that they were not considered either out of lack of knowledge or a standard of care.

6. Additional Violations and/or Structural Problems with WTC 7

(i) Complex Nature of the Building. The site constraints made the structure of WTC 7 unique and challenging. Building around and above an existing operational vault and building new foundations and superstructure requires a heightened level of care. The difficulty in the structural design was compounded by the location in Southern Manhattan which had witnessed bombings in the years prior to and during the design and construction of WTC 7. The provision of a truck ramp under the east bay of the tower, introduced the possibility of fire or bomb undermining the integrity of the building.

All these factors necessitated a higher degree of expertise, design considerations and care in the design of this structure. It is my opinion that this was not done in the design of WTC 7.

(ii) Lack of Lateral Systems: Classical tall building design for a 47 story building uses a "tube-in-tube" system. Essentially the braced core (inner tube) should have been taken all the way to the top of the building (instead of just to the 7^{th}

floor, as it was at WTC 7) just as the exterior "tube" of welded girders and columns was taken to the roof. This would have been particularly helpful to provide lateral bracing support to the building diaphragm, fragmented by the trench headers.

(iii) Trench Headers: The floor slabs perform the function of a floor diaphragm tying the structure together. This diaphragm is needed to provide in-plane bracing connection of columns to lateral load resisting elements to transmit wind forces from the façade to the perimeter "tube", and to transmit the bracing force for interior columns.

In the location of the trench header there is no concrete slab and hence the welding of the metal deck is crucial. A critical detail such as this, should have been shown on the structural drawings. .

A good engineer would have not only shown the reinforcement of the deck for the trench header but also provided the in-floor diagonal bracing to transmit diaphragm forces (see Figs. 6.1 and 6.2)

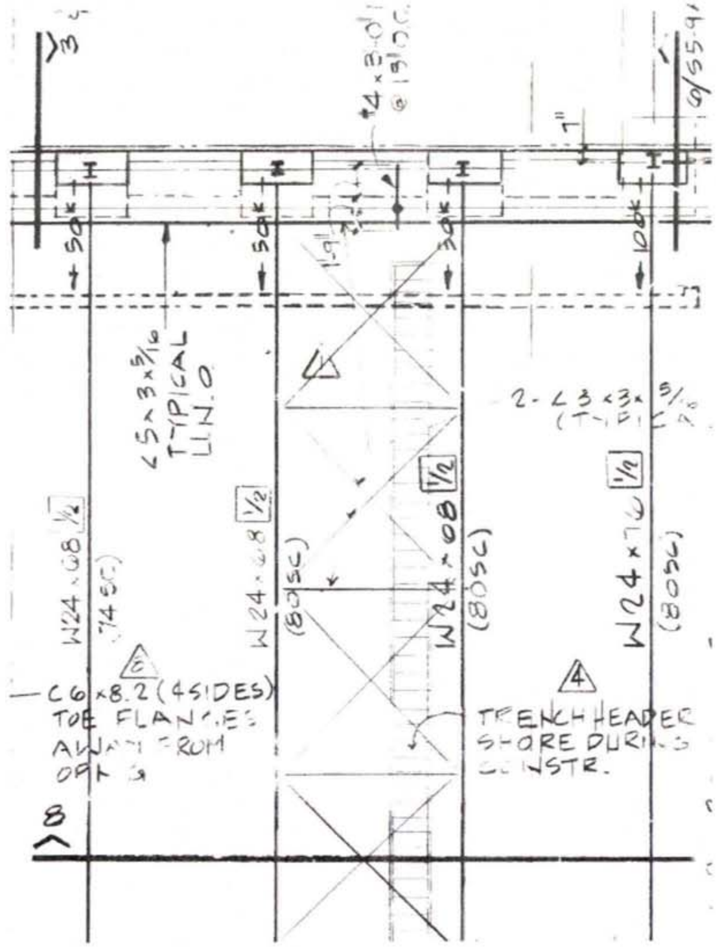


Figure 6.1 Partial Plan View showing Trench Header on a 1978 project in Houston Texas, designed by CBM Engineers

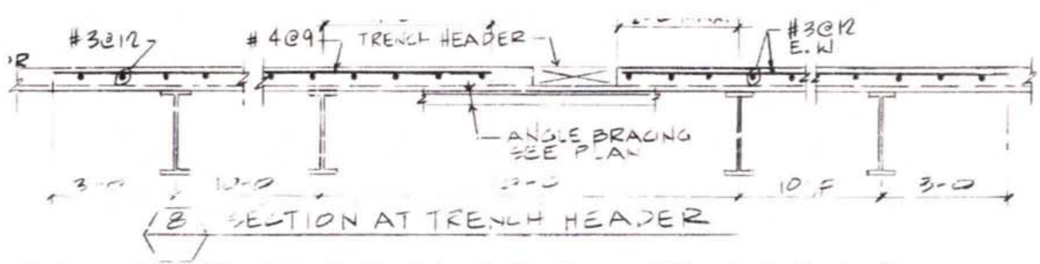


Figure 6.2 Section View of Trench Header Detail showing Bracing on a 1978 project in Houston Texas, designed by CBM Engineers

(iv) Transfer Girders: The deep transfer girders for the north face columns have two problems. First a transfer girder is a poor choice compared to an inclined column. Fig. 6.3 shows the inclined column transfer was used on 560 Mission in San Francisco.

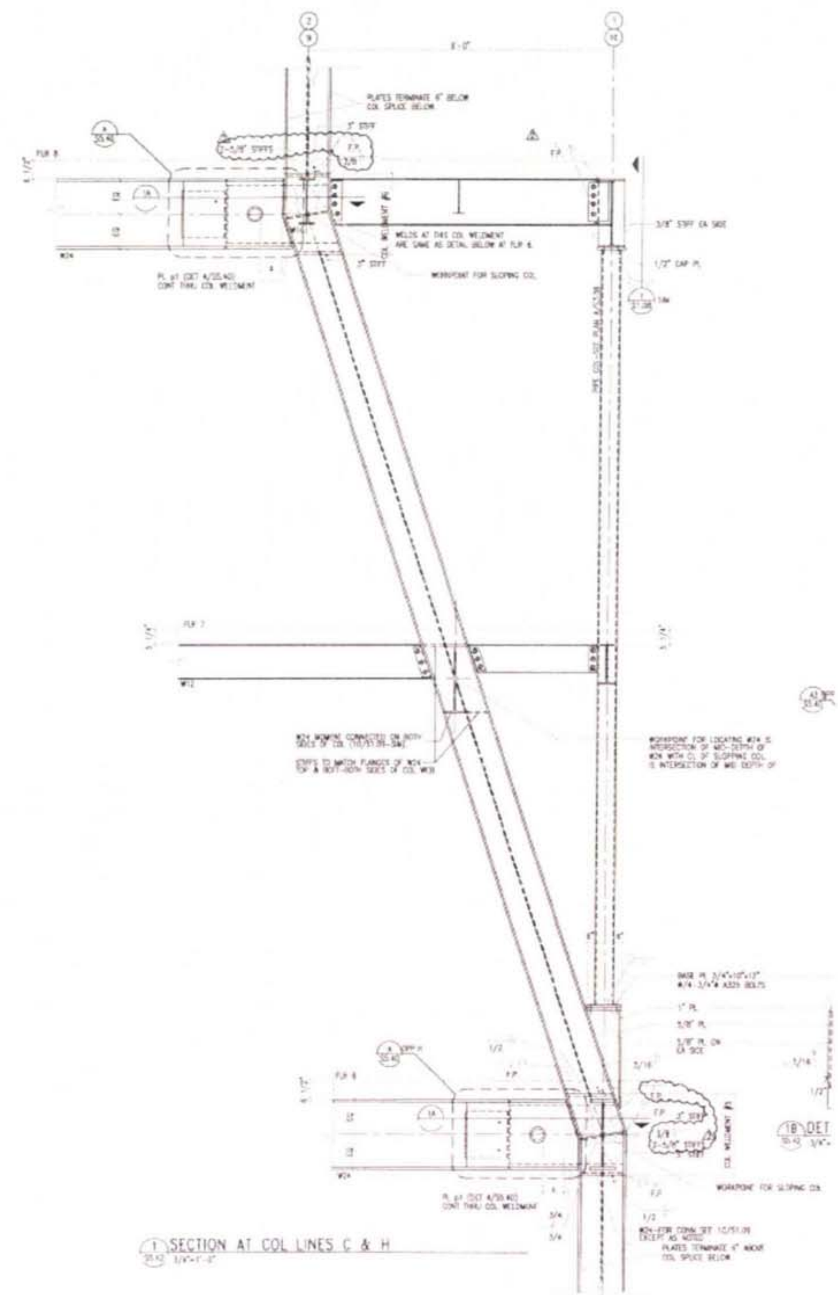


Figure 6.3 Inclined Column used in 560 Mission Building designed by CBM Engineers

Secondly in the case of the girders for columns 45 and 46, they create dual transfers. The transfer girder is itself further transferred by Truss 1. In my opinion stacking of transfer systems increases the vulnerability of the overall structure since any problem with the members or connections in Truss 1 will also affect the north face of WTC 7.

(v) Differential Loading in Exterior Columns

Based on their tributary areas, 43 and 27 did not take much floor load (Fig 6.4 and Fig 6.6). The columns next to them, 44 and 26, take a significantly higher tributary load. Yet, columns 44 and 43 are of the same size according to the column schedule in the construction documents (Figure 6.5). A similar loading situation occurs with respect to columns 26 and 27 (Fig 6.7). In that case, the columns with the smaller tributary load are of larger size. This type of member sizing is problematic in tall building design because it creates differential axial shortening under gravity loads. A consequence of this effect is that the column loads in the perimeter moment frame are redistributed, creating differences between the theoretical and actual axial loads in these members. This variation is confirmed by the differences observed between the perimeter column axial loads listed in the project engineer's column schedule and those shown in our global ETABS model. An additional repercussion of this effect is described in the following section on the belt trusses.

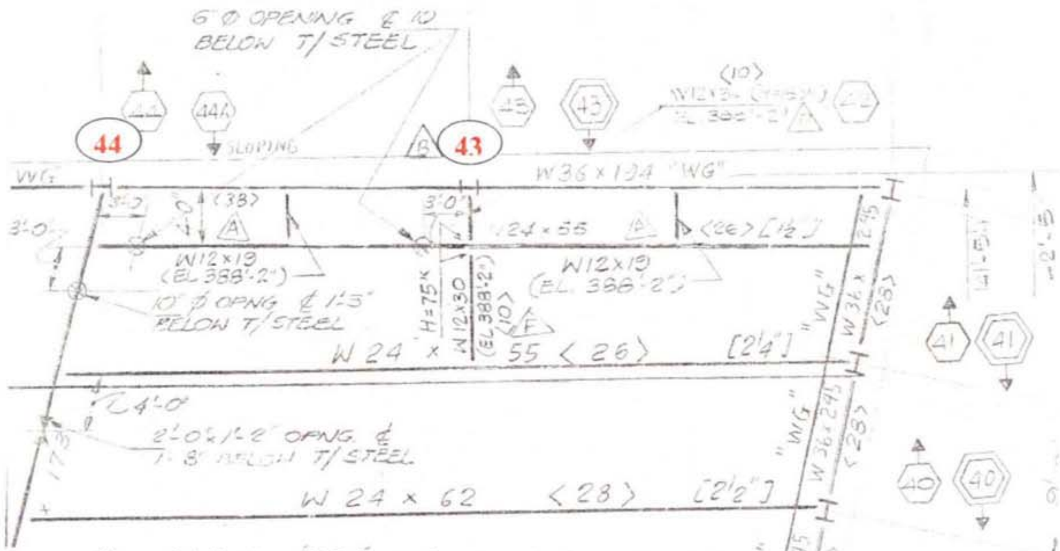


Figure 6.4 Portion of S-7 showing location of columns 43 and 44 in the northeast corner

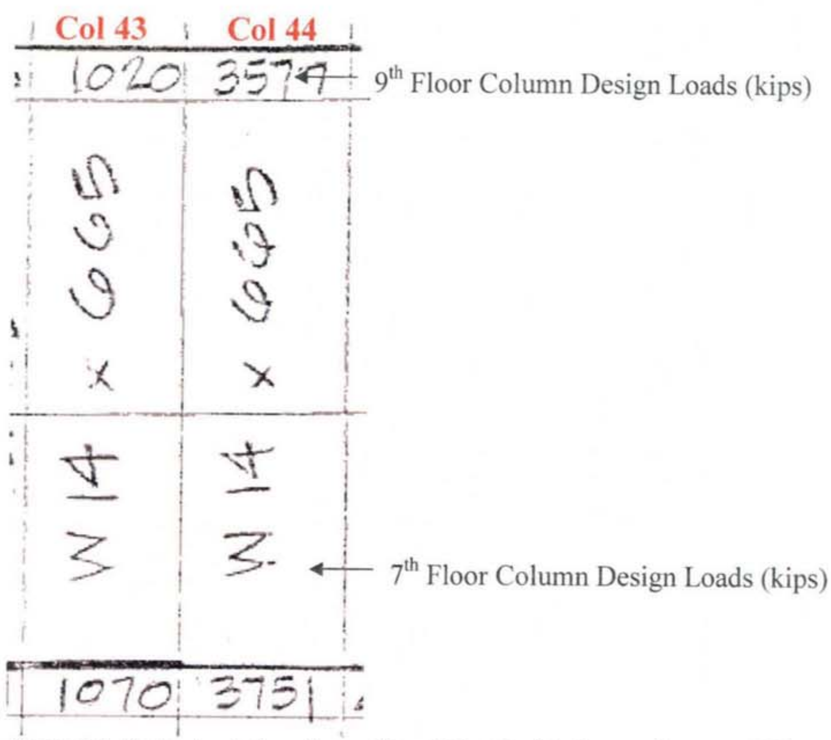


Figure 6.5 Design loads for columns 43 and 44 at the 7th floor as shown on S-17

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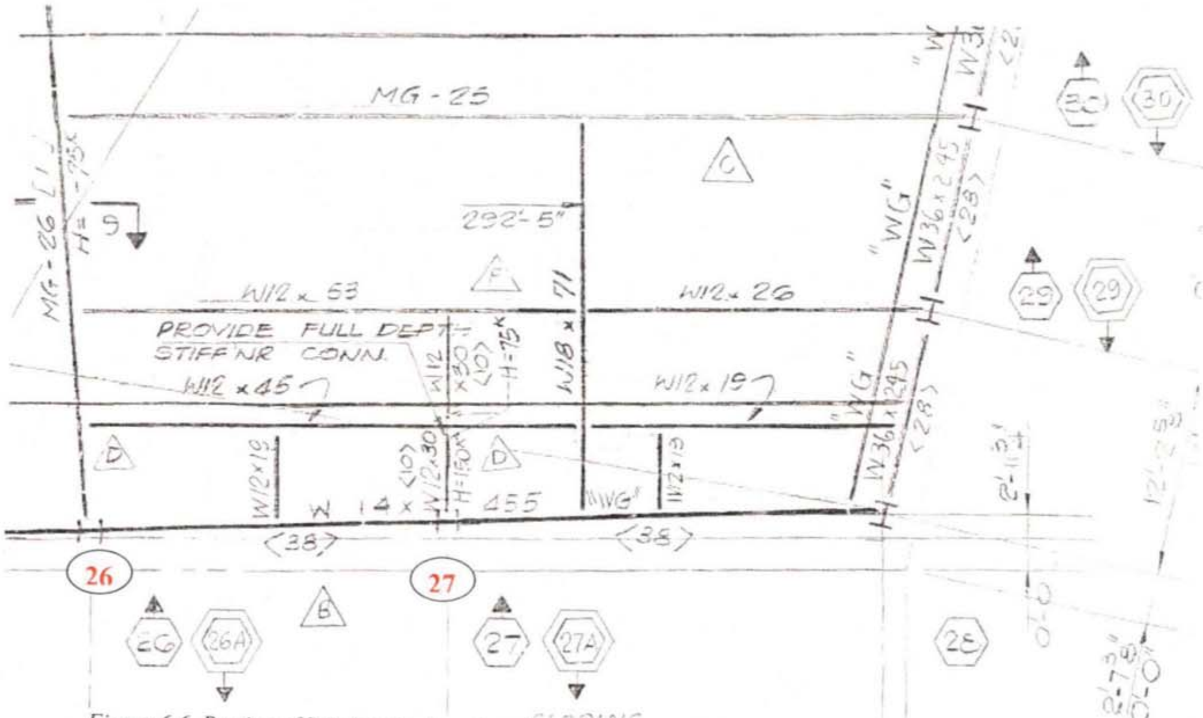


Figure 6.6 Portion of S-7 showing location of columns 26 and 27 in the southeast corner

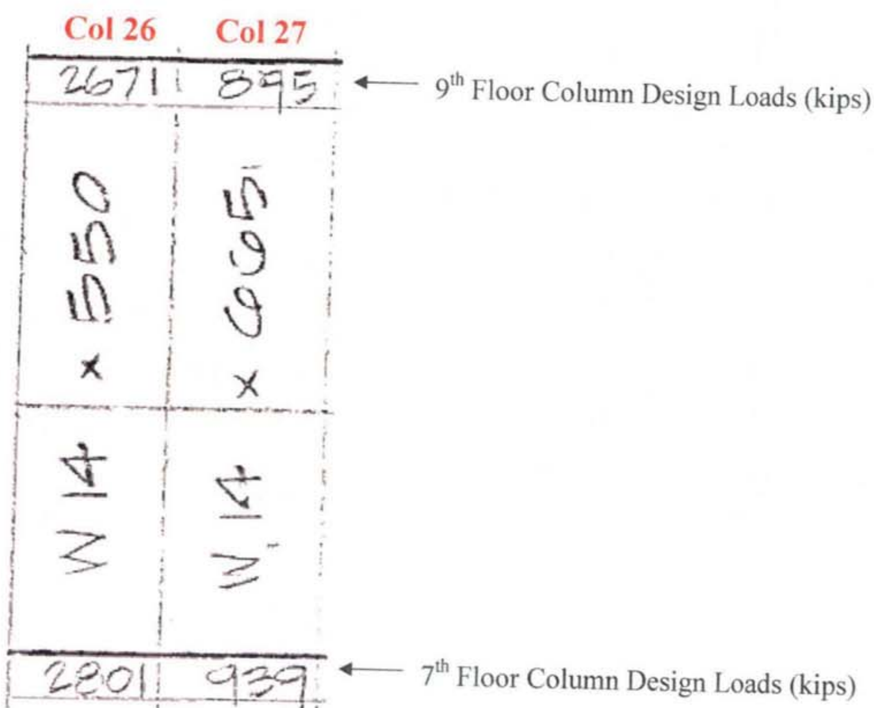


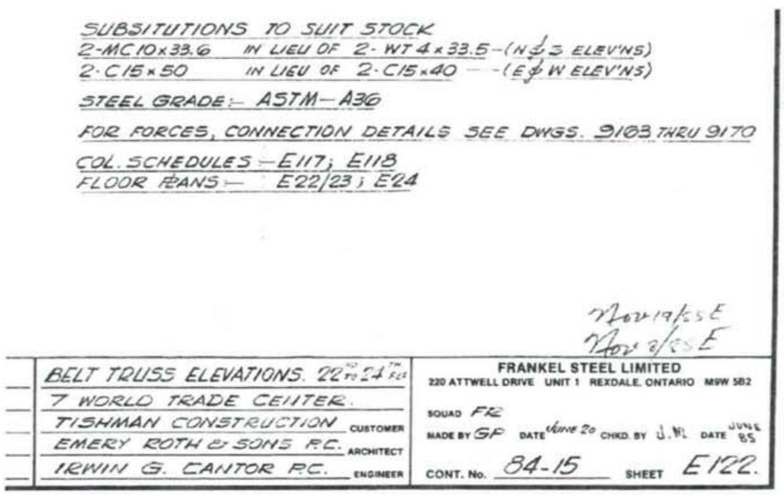
Figure 6.7 Design loads for columns 26 and 27 at the 7th floor as shown on S-17

(vi) Belt Trusses and Wind Bracing Systems

From the 22nd to 24th floors, there were diagonal members connecting exterior columns. These members form a "belt truss". The primary purpose of the truss is to stiffen the exterior frame for lateral deflection of the building under wind loads.

If the exterior columns are properly sized such that the axial stresses under gravity loads were the same, then no stresses would have been induced in the belt truss diagonals under gravity loads. However, as previously mentioned, in WTC 7 the column sizes were not selected in this manner. As a result, gravity stresses were induced in the diagonals. This resulted in the diagonals being overstressed.

Wind bracing systems were examined by a code check. Over-stressed members in the wind braces are shown in red in the figures below. It is noted that Frankel steel changed the belt truss diagonal sections due to stock availability (Fig 6.8) and the change was reflected in the ETABS model for code check.


SUBSITUTIONS TO SUIT STOCK
2-MC10x33.6 IN LIEU OF 2-WT4x33.5-(N & S ELEV'NS)
2-C15x50 IN LIEU OF 2-C15x40 --(E & W ELEV'NS)
STEEL GRADE:- ASTM-A36
FOR FORCES, CONNECTION DETAILS SEE DWGS. 9103 THRU 9170
COL. SCHEDULES -E117; E118
FLOOR PLANS - E22/23; E24
Nov 19/85 E
Nov 8/85 E

BELT TRUSS ELEVATIONS. 22ND TO 24TH FLS
7 WORLD TRADE CENTER.
TISHMAN CONSTRUCTION CUSTOMER
EMERY ROTH & SONS P.C. ARCHITECT
IRWIN G. CANTOR P.C. ENGINEER

FRANKEL STEEL LIMITED
220 ATTWELL DRIVE UNIT 1 REXDALE, ONTARIO M9W 5B2
SQUAD FR
MADE BY GP DATE June 20 CHKD. BY J.M. DATE JUNE 85
CONT. No. 84-15 SHEET E122.

Figure 6.8 Substitution to Suit Stock excerpt from Frankel Steel Shop Dwg. E122

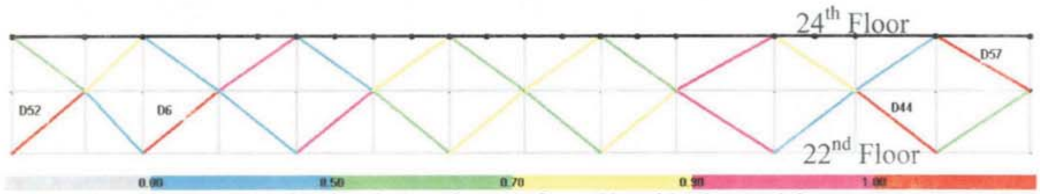


Figure 6.9 South Belt Truss between floors 22 and 24 diagonal diagram

Table 6.1 South Belt Truss between floors 22 and 24 Stress Ratios

Story	Brace ID	Brace Section	ETABS Stress Ratio
23	D6	2MC10X33.6	1.597
23	D44	2WT5X56	1.578
23	D52	2WT5X56	1.786
24	D57	2WT5X56	1.623

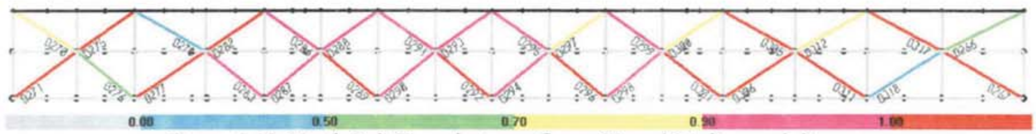


Figure 6.10 North Belt Truss between floors 22 and 24 diagonal diagram

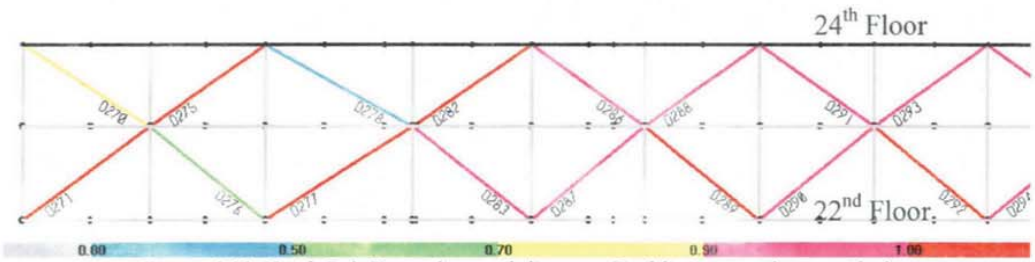


Figure 6.11 North Belt Truss diagonal diagram (Building east side magnified)

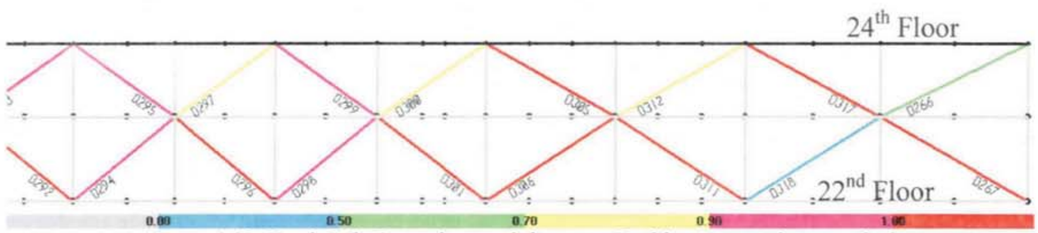


Figure 6.12 North Belt Truss diagonal diagram (Building west side magnified)

Table 6.2 North Belt Truss between floors 22 and 24 Stress Ratios

Story	Brace ID	Brace Section	ETABS Stress Ratio
23	D267	2WT5X56	1.833
23	D271	2WT5X56	1.475
24	D275	2WT5X56	1.595
24	D282	2MC10X33.6	1.095
23	D289	2MC10X33.6	1.026
23	D292	2MC10X33.6	1.07
23	D296	2MC10X33.6	1.094
23	D301	2MC10X33.6	1.145
24	D305	2WT5X56	1.093
23	D306	2WT5X56	1.01
23	D311	2WT5X56	1.141
24	D317	2WT5X56	1.725

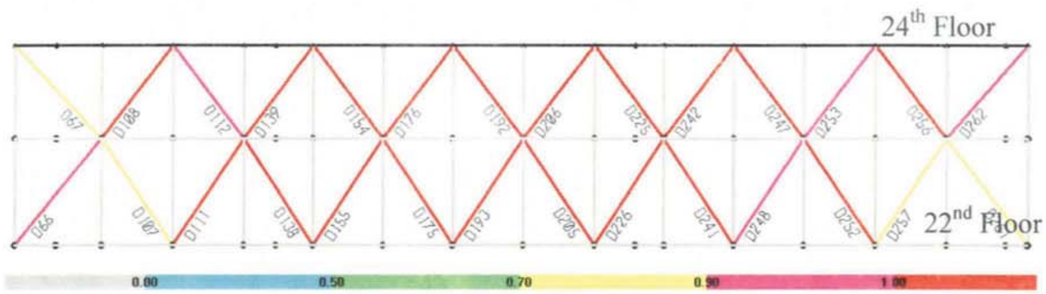


Figure 6.13 East Belt Truss between floors 22 and 24 diagonal diagram

Table 6.3 East Belt Truss between floors 22 and 24 Stress Ratios

Story	Brace ID	Brace Section	ETABS Stress Ratio
24	D108	2C15X33.9	1.084
23	D111	2C15X33.9	1.717
23	D138	2C15X50	1.032
24	D139	2C15X50	1.475
24	D154	2C15X50	1.114
23	D155	2C15X50	1.783
23	D175	2C15X50	1.392
24	D176	2C15X50	1.483
24	D192	2C15X50	1.336
23	D193	2C15X50	1.589
23	D205	2C15X50	1.716
24	D206	2C15X50	1.225
24	D225	2C15X50	1.595
23	D226	2C15X50	1.259
23	D241	2C15X50	1.912
24	D242	2C15X50	1.004
24	D247	2C15X50	1.539
23	D252	2C15X33.9	1.725
24	D256	2C15X33.9	1.036

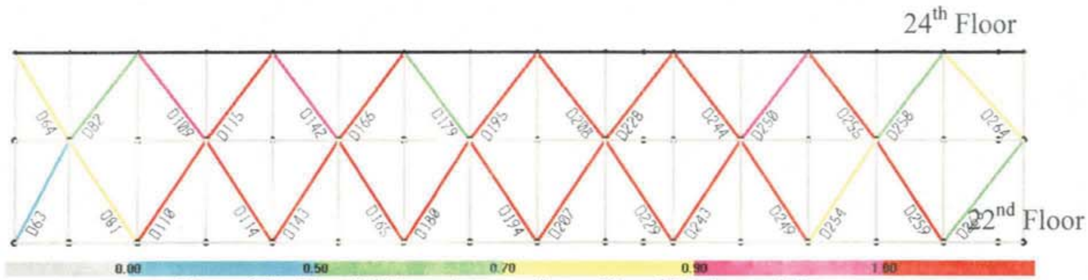


Figure 6.14 West Belt Truss between floors 22 and 24 diagonal diagram

Table 6.4 West Belt Truss between floors 22 and 24 Stress Ratios

Story	Brace ID	Brace Section	ETABS Stress Ratio
23	D110	2C15X50	1.227
23	D114	2C15X50	1.022
24	D115	2C15X50	1.164
23	D143	2C15X50	1.655
23	D165	2C15X50	1.021
24	D166	2C15X50	1.484
23	D180	2C15X50	2.307
23	D194	2C15X50	1.506
24	D195	2C15X50	1.513
23	D207	2C15X50	1.634
24	D208	2C15X50	1.335
24	D228	2C15X50	1.228
23	D229	2C15X50	1.268
23	D243	2C15X50	1.289
24	D244	2C15X50	1.104
23	D249	2C15X50	1.557
24	D255	2C15X33.9	1.39
23	D259	2C15X33.9	1.554

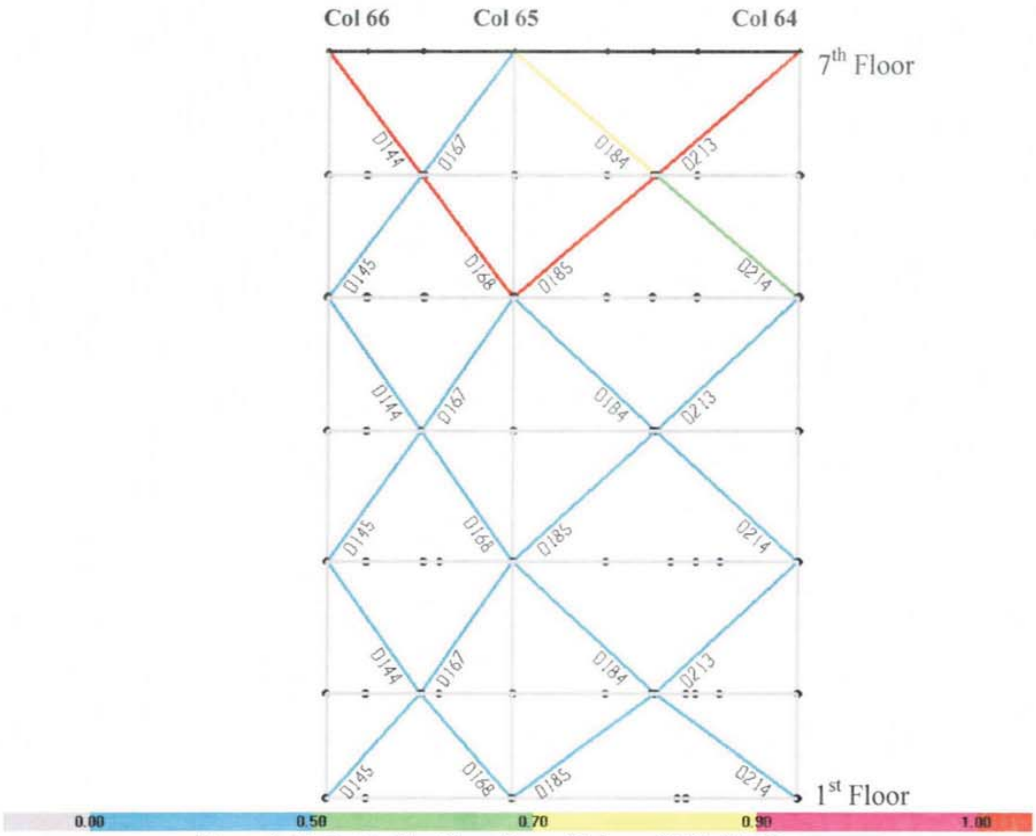


Figure 6.15 East to West Core Brace (Column 66-65-64) Diagram

Table 6.5 East to West Core Brace (Column 66-65-64) Stress Ratios

Story	Brace ID	Brace Section	ETABS Stress Ratio
7	D144	2C12X30	2.05
6	D168	2C12X30	1.71
6	D185	2C12X30	1.896
7	D213	2C12X30	1.768

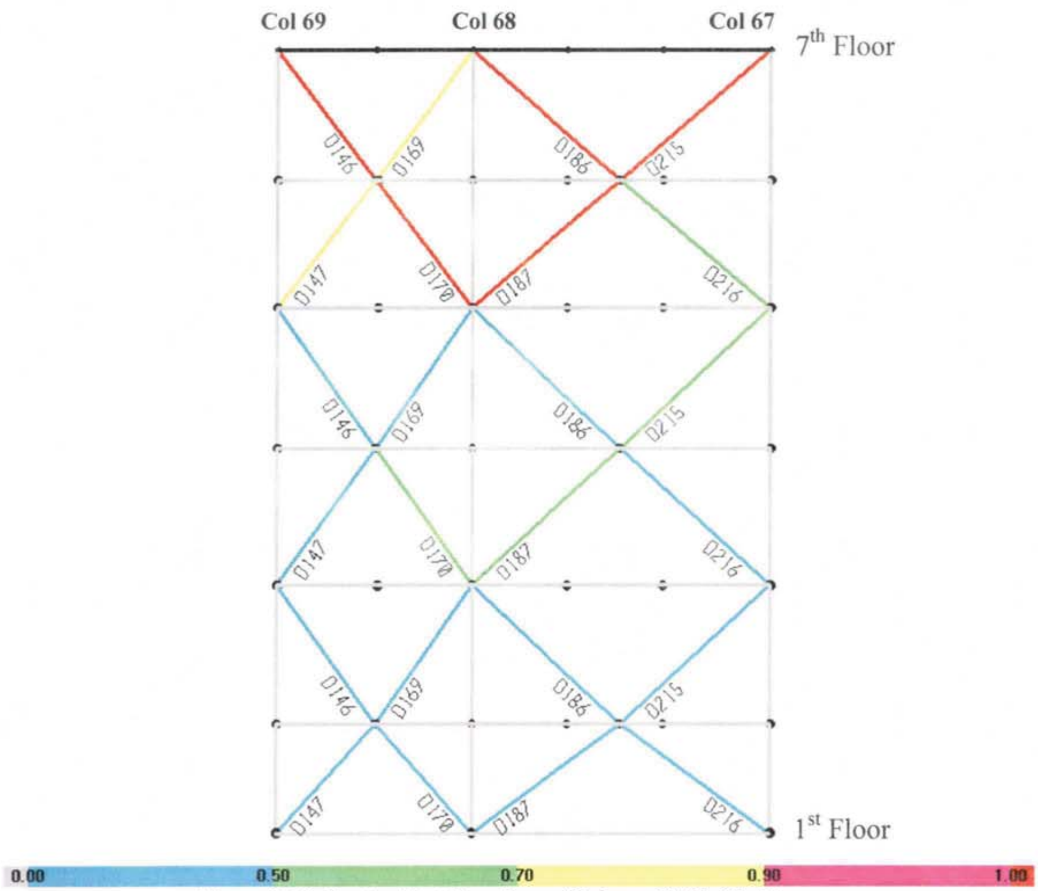


Figure 6.16 East to West Core Brace (Column 69-68-67) Diagram

Table 6.6 East to West Core Brace (Column 69-68-67) Stress Ratios

Story	Brace ID	Brace Section	ETABS Stress Ratio
7	D146	2C12X30	1.986
6	D170	2C12X30	1.669
7	D186	2C12X30	1.016
6	D187	2C12X30	2.189
7	D215	2C12X30	1.964

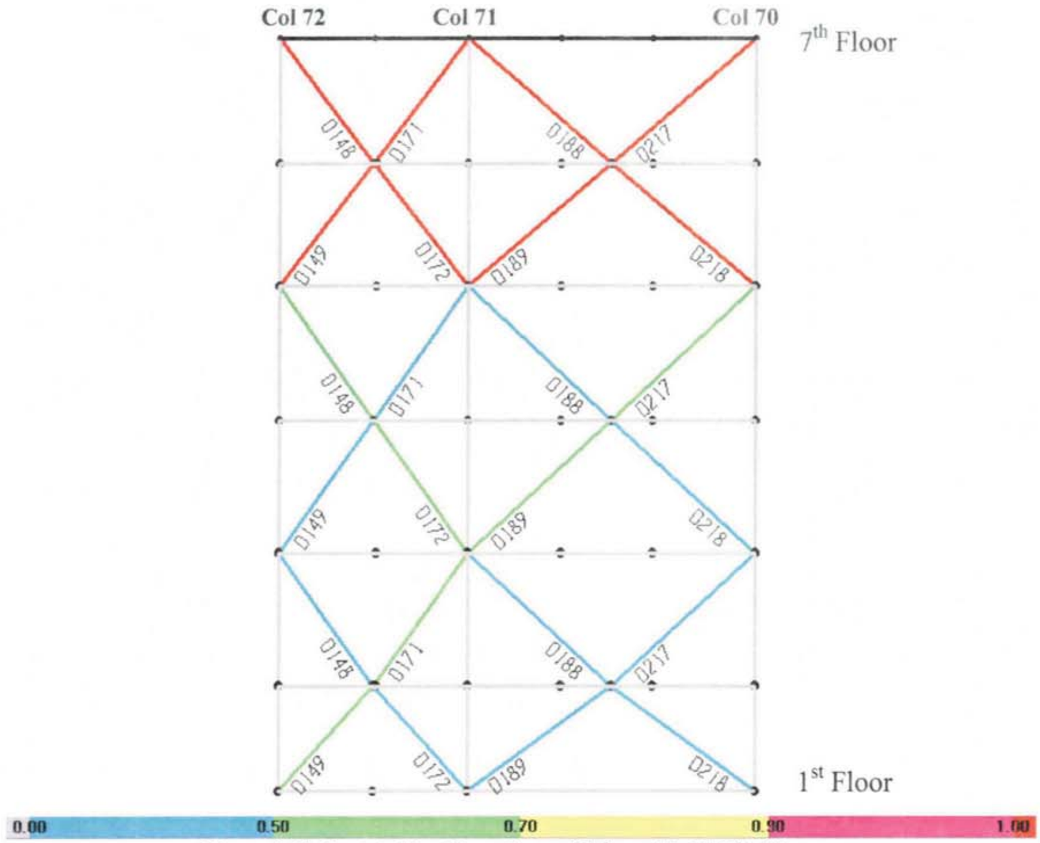


Figure 6.17 East to West Core Brace (Column 72-71-70) Diagram

Table 6.7 East to West Core Brace (Column 72-71-70) Stress Ratios

Story	Brace ID	Brace Section	ETABS Stress Ratio
7	D148	2C12X30	2.075
6	D149	2C12X30	1.277
7	D171	2C12X30	1.373
6	D172	2C12X30	1.796
7	D188	2C12X30	1.637
6	D189	2C12X30	2.112
7	D217	2C12X30	1.771
6	D218	2C12X30	1.013

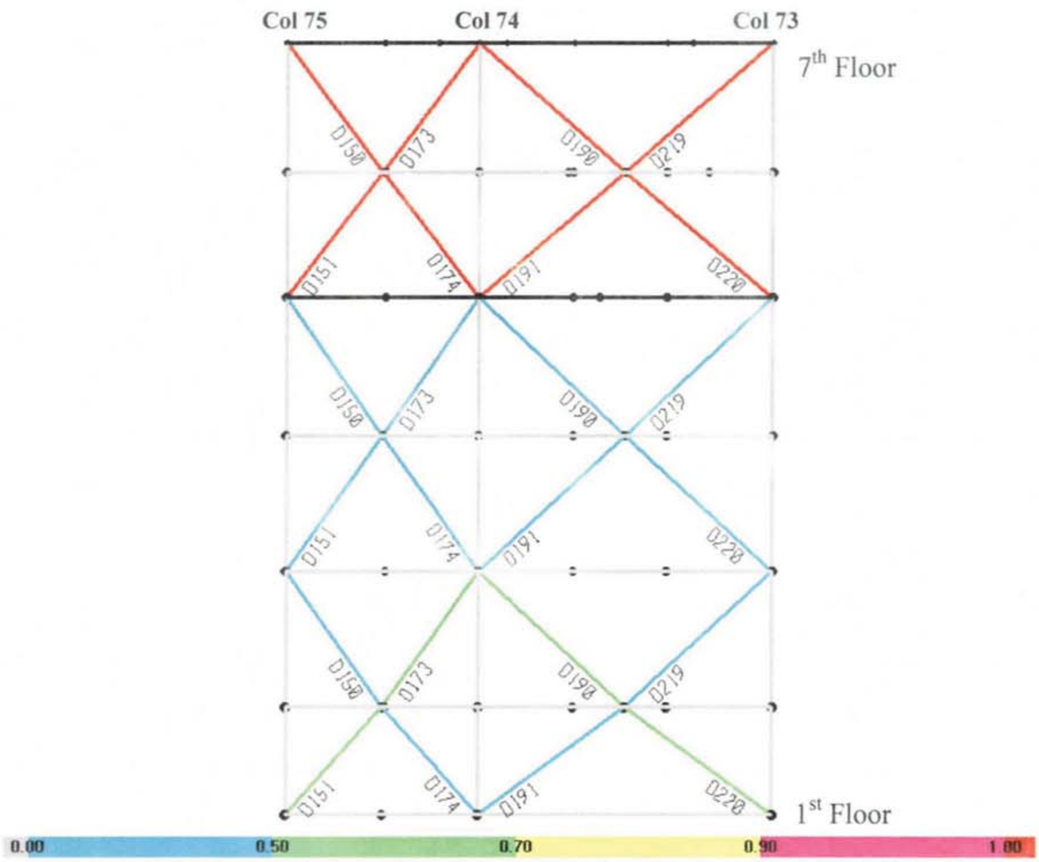


Figure 6.18 East to West Core Brace (Column 75-74-73) Diagram

Table 6.8 East to West Core Brace (Column 75-74-73) Stress Ratios

Story	Brace ID	Brace Section	ETABS Stress Ratio
7	D150	2C12X30	2.307
6	D151	2C12X30	1.687
7	D173	2C12X30	1.286
6	D174	2C12X30	1.272
7	D190	2C12X30	2.299
6	D191	2C12X30	1.451
7	D219	2C12X30	1.132
6	D220	2C12X30	1.509

As seen in the figures and tables above, the majority of the diagonals in the belt trusses and the diagonals between level 5 and 7 in the east to west core braces show stress ratios greater than 1.0. The diagonals also have higher axial forces than the design forces indicated in Cantor structural drawing S-22. It is observed in the ETABS analysis output that gravity loads are picked up by the diagonals and this primarily leads to the over-stressed diagonals combined with wind loads. It is not clear whether the Cantor design loads indicate axial loads caused by wind load only or by combined wind and gravity loads. In addition, bracing connection details do not show any structural attempts to release the gravity loads on the diagonals. Allowable stresses have already increased by a factor of 4/3 of the regular allowable value when code-checking for load combinations involving wind load.

(vii) <u>Connection Design by Engineer of Record for a unique and complicated building, it is incumbent that the Engineer of Record:</u>

- Fully design critical connections such as those for transfer trusses and transfer girders, etc.
- For other critical connections such as welding of metal deck at trench headers, and girder to column connections, the type of connection to be used and ALL forces on the connection should be clearly enumerated.

In the case of WTC 7, this important function was relegated to the steel fabricator. In my opinion this does not meet the standard of care.

(viii) Design of Structure at the Truck Ramp: It was discussed above that the twin potential threats at the truck ramp are a fire and/or blast.

It is this writer's opinion, all the columns and the structure around and above the truck ramp should have been designed for the twin threats. The columns should have been hardened by concrete encasement and the structure immediately above the truck ramp should have been designed for blast loading.

(ix) Recommended minimum size of fillet weld by Blodgett and AWS: Blodgett and AWS have recommended the minimum size of fillet welds as per Table 3 in his book (Fig. 6.19) instead of Table 1.17.2A in *AISC Manual 8th Edition.* This will require minimum 5/8" fillet welds for 6" thick plate compared to 5/16".

TABLE 3—Minimum Weld Sizes for Thick Plates (AWS)

THICKNESS OF THICKER PLATE JOINED t	MINIMUM LEG SIZE OF FILLET WELD ω
to 1/2" Incl.	3/16"
over 1/2" thru 3/4"	1/4"
over 3/4" thru 1 1/2"	5/16"
over 1 1/2" thru 2 1/4"	3/8"
over 2 1/4" thru 6"	1/2"
over 6"	5/8"

Minimum leg size need not exceed thickness of the thinner plate.

Figure 6.19 Table 3 Excerpt from Design of Weldments by Omer W. Blodgett in 1963

Most of the built-up shapes, columns, plate girders and trusses are made with thick cover plates welded to jumbo shapes using only 5/16" fillet welds. For column 79 between 1st and 3rd floor, two 5 inch thick cover plates were welded to W14X730 with 5/16" fillet welds (Fig 6.20). According to the table shown above (Fig 6.19), 1/2" fillet weld is required. A prudent engineer would have used thicker than 5/16" fillet welds for thick plates and shapes.

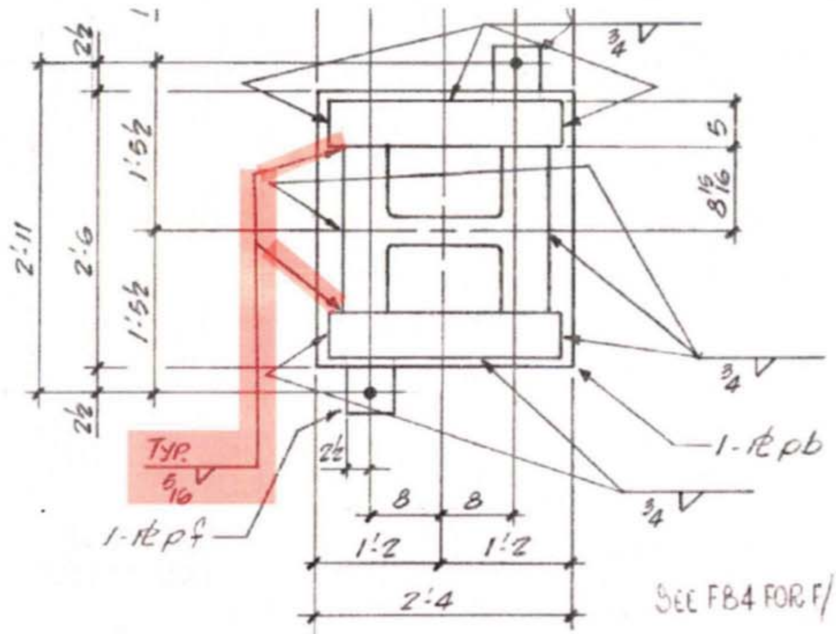


Figure 6.20 Excerpt from Frankel Steel Shop Drawing #59 Showing Column 79 Detail

7. Global Conclusion

WTC 7 was not built in accordance with the standards of good engineering practice. Proper design for structural integrity would have prevented the initial failure and the global collapse. A prudent engineer should have recognized such design requirements at the time of the design and construction of WTC 7. Design modifications proposed in this report would have been relatively inexpensive and would have yielded several additional benefits not related to the collapse of September 11, 2001. Finally, the terrorist attack in 1993 should have precipitated a review of the structural design and modifications to address its deficiencies.

Joseph P. Colaco

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