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Appendix I
INTERIM REPORT ON ASSESSMENT OF SPRAYED FIREPROOFING IN THE WTC TOWERS—METHODOLOGY

I.1 INTRODUCTION

The structural steel in the World Trade Center (WTC) towers was "fireproofed" with sprayed fire resistive materials (SFRMs). These materials are packaged as dry ingredients, and water is added by a pressurized system as the materials are sprayed onto the steel. The water mixes with the cementitious materials and provides "stickiness" that allows the SFRM to adhere weakly to the steel. With time, the cementitious materials harden, and excess water evaporates. When dry, SFRMs provide an insulation barrier to reduce the vulnerability of the steel to excessive temperature rise during a fire.

Analysis of the effects of the fires on the structural capacity of the damaged WTC towers as a function of time requires knowledge about the condition of fireproofing on the various structural components, namely, the exterior columns, the spandrel beams, the floor trusses, and the core columns. Because of the method of application, sprayed fireproofing will have variable thickness, especially when applied to long, thin elements such as the diagonals and chords of the floor trusses. In addition, fireproofing was dislodged during the impact, either from direct impact by debris or from vibrations of the members. The thermal properties of the fireproofing also need to be known as a function of temperature.

The thermal-structural analysis of the WTC towers focused on two objectives: (1) analysis of the undamaged buildings exposed to postulated fires, and (2) analysis of damaged buildings exposed to the fires that occurred after impact. In order to reduce the uncertainties in the calculated thermal histories of various structural elements, the condition of the sprayed fireproofing as it existed on September 11, 2001, needs to be estimated as accurately as possible. In addition, reasonable estimates of the extent of fireproofing dislodged by the aircraft are needed. This appendix discusses the approach that will be used for this purpose.

To gain an understanding of the effect of fireproofing thickness and its variability on the steel temperature during exposure to fire, a simple finite-element model was used for a sensitivity study. The information gained from that study is reviewed first. A brief summary of the construction history of the sprayed fireproofing in WTC 1 and WTC 2 is presented. This is followed by a quantitative assessment of in-place thickness and its variability based on available data. The rationale for the thickness of fireproofing to be used in the structural fire endurance analyses is presented. The tests conducted to determine the thermal properties of fireproofing materials similar to those used in the WTC towers are reviewed. The approach used to gain an understanding of the inherent fragility of sprayed fireproofing is discussed, and the scheme for estimating the extent of damage during impact is summarized.

I.2 SENSITIVITY OF THERMAL RESPONSE TO FIREPROOFING GEOMETERY

The fireproofing thickness has a great effect on the thermal response of the structural elements for a given fire condition. While others have considered the effect of thickness of fireproofing, the effect of the variation of thickness along the length of a member is not well known. A sensitivity study using finite element modeling of heat transfer was conducted to investigate the sensitivity of steel temperature to the variability in fireproofing thickness.

The simplified model that was used is shown in Fig. I–1. A 1 in. thick, 60 in. long steel plate (cyan color) was coated with fireproofing material (purple color) and subjected to the uniform radiative flux arising from a 1,100 °C fire. As shown in Fig. I–1 (b), the fireproofing is modeled with a layer of finite elements (0.125 in. thick and 0.6 in. long) having the thermal properties of fireproofing (purple). A parametric study was conducted with average thickness of fireproofing varying from 0 in. to 2 in. in increments of 1/4 in. The effect of variability in thickness was modeled by imposing a normal probability distribution on the fireproofing thickness along the length of the steel plate. The assumed standard deviation varied from 0 in. (uniform thickness) to 1 in. A psuedo-random number generator was employed to determine the thickness at each cross section based on the assumed average thickness and standard deviation. The layer representing fireproofing was taken to be twice the average thickness, and the thickness of fireproofing at any cross section was modeled by assigning a low heat capacity and a high thermal conductivity to those elements that do not provide fireproofing. Figure I–1 (c) shows an example of variable thickness fireproofing; in this case, the average thickness is 1 in. and the standard deviation is 3/8 in.

When the model in Fig. I–1 is exposed to the thermal flux representing an 1,100 °C fire, the surface of the insulation heats up quickly to the gas temperature (1,100 + 273 = 1,373 K). Numerical simulation was performed over a 2-h period, and the steel temperature at five locations was recorded at 30 min, 60 min, 90 min, and 120 min of exposure. The temperature recording locations are 6 in. from each end and at 12 in. intervals, which are shown as numbers 1 to 5 in Fig. I–1 (a). The initial temperature of the model is 300 K.

Figure I–2 shows temperature contours (in K) through the fireproofing and steel at 60 min after initial exposure for the model shown in Fig. I–1 (a). The fireproofing surface temperature is close to the gas temperature of 1,373 K, while the steel temperature is 311 K. If the fireproofing were of uniform thickness, the isotherms would be a series of lines parallel to the plate. It is seen that, when the thickness of fireproofing is variable, the isotherms follow the shape of the fireproofing surface contour. Thus, the temperature history at any point in the steel depends on the loc al thickness of the fireproofing.

Figure I–3 shows the steel temperature at the far sensor #1 (6 in. from the end) as a function of time for various insulation thicknesses ranging from 0 in. to 2 in. (the thickness is indicated by the numbers on the curves). For the case in Fig. I–3 (a), the fireproofing is of uniform thickness, and for the cases in Fig. I–3 (b), the thickness varies with a standard deviation of 1 in. The time to reach a temperature of 600 °C is used as a measure of relative performance. It is seen that the presence of high variability in thickness has a detrimental effect of the protection provided by the fireproofing. For example, for a uniform thickness of 0.5 in., it takes about 60 min for the steel at point #1 to reach 600 °C; but when the standard deviation of the thickness is 1 in., the average thickness has to be 1.75 for the same level of thermal protection.

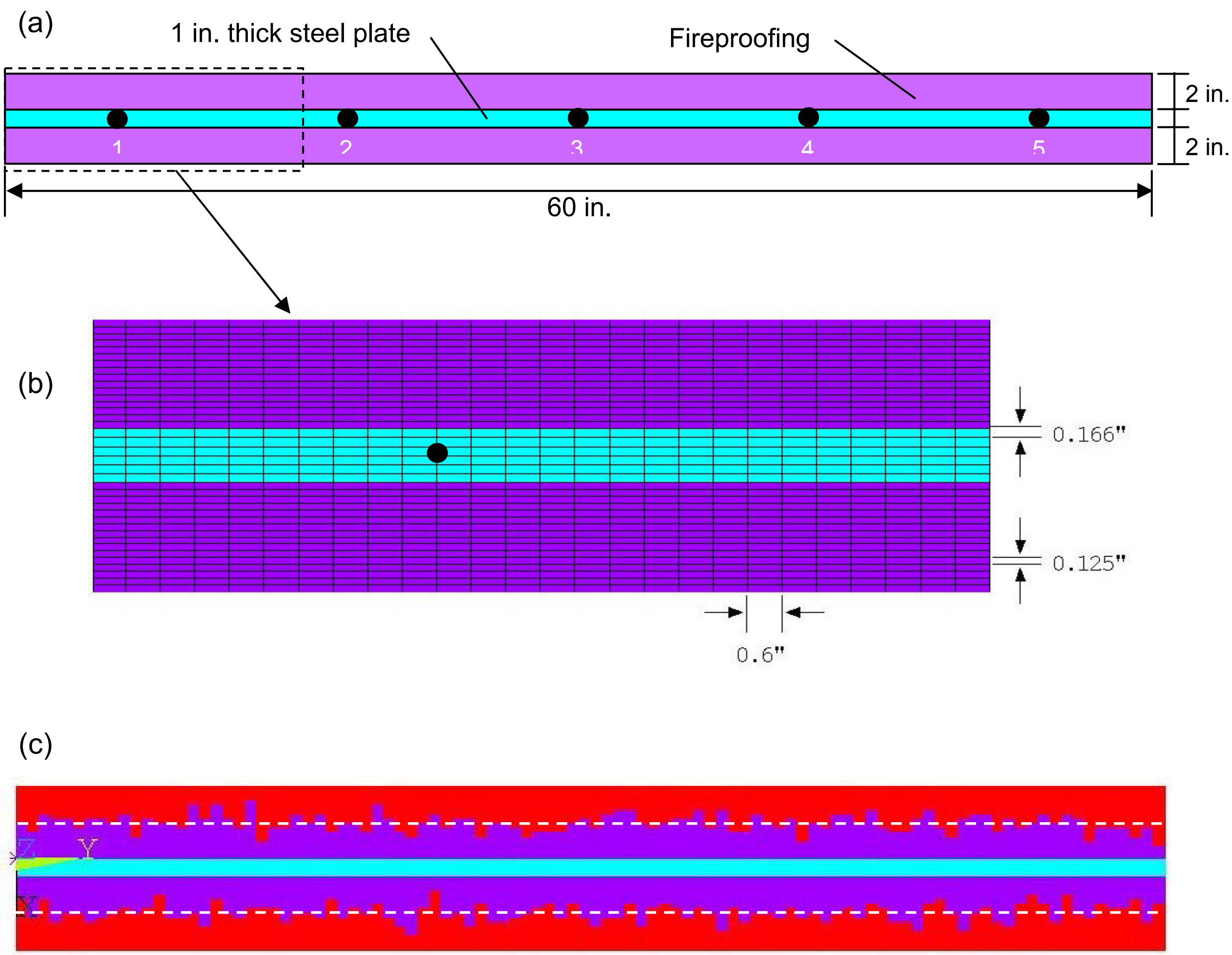


Figure I–1. Model used to study effects of fireproofing thickness and variability of thickness on steel temperature: (a) physical model used in analyses (points 1 to 5 are locations where temperatures are monitored), (b) finite element mesh used to represent physical model, and (c) finite element model to represent variable thicknessof fireproofing (purple) (the elements in red represent material of high thermal conductivity).

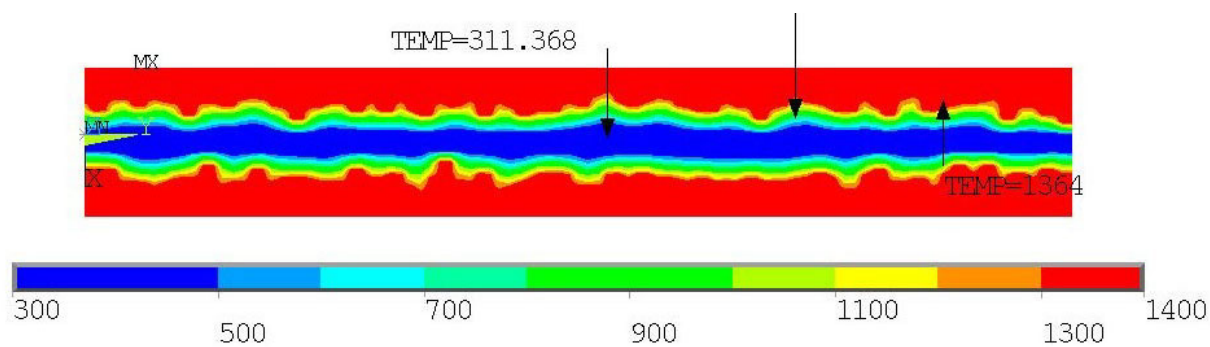


Figure I–2. Temperature distribution after 1 h of exposure to gas temperature of 1,100 °C (1,373 K).

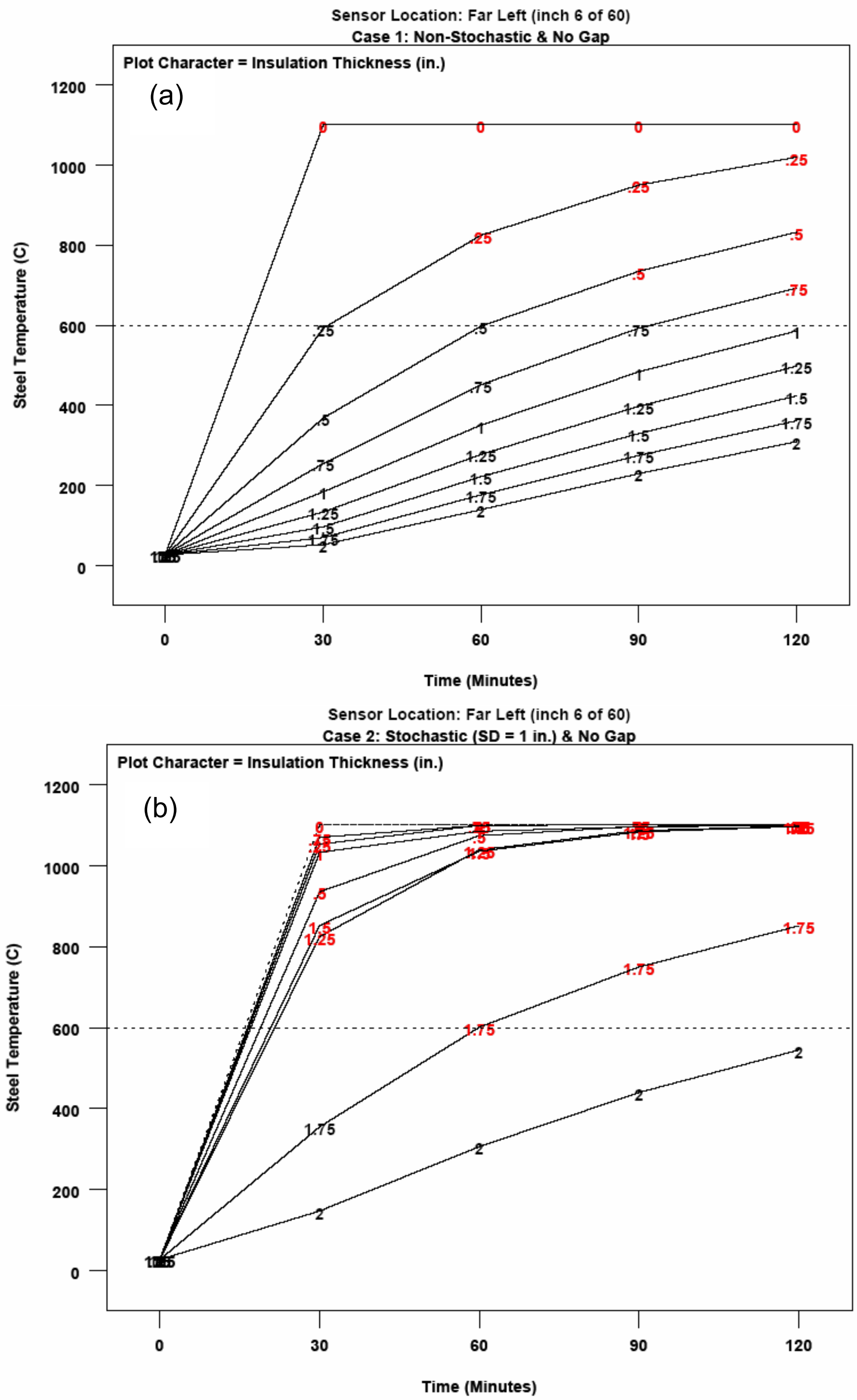


Figure I–3. Variation of steel temperature (at a point 6 in. from end of plate) with time for different average thicknesses of fireproofing (shown as numbers on the curves): (a) uniform thickness, and (b) variable thickness with a standard deviation of 1 in.

In addition to the effect of variation in thickness, it is important to understand the effect of missing fireproofing over a portion of a member. As an example, Fig. I–4 shows missing fireproofing from a diagonal of a bridging truss of the WTC towers floor system. Figure I–5 (a) shows an example of a numerical model with missing fireproofing. In this case, there is 12 in. of missing fireproofing on the steel plate, which is otherwise protected by 2 in. of uniform thickness fireproofing. Figure I–5 (b) shows the temperature contours (isotherms) at time 50 min. For comparison, Fig. I–5 (c) shows isotherms at the same time in a plate with no gap in the fireproofing. As expected, the bare steel at the missing fireproofing is at the gas temperature, but more importantly the "gap" in fireproofing leads to a "leakage" of heat into the interior steel.

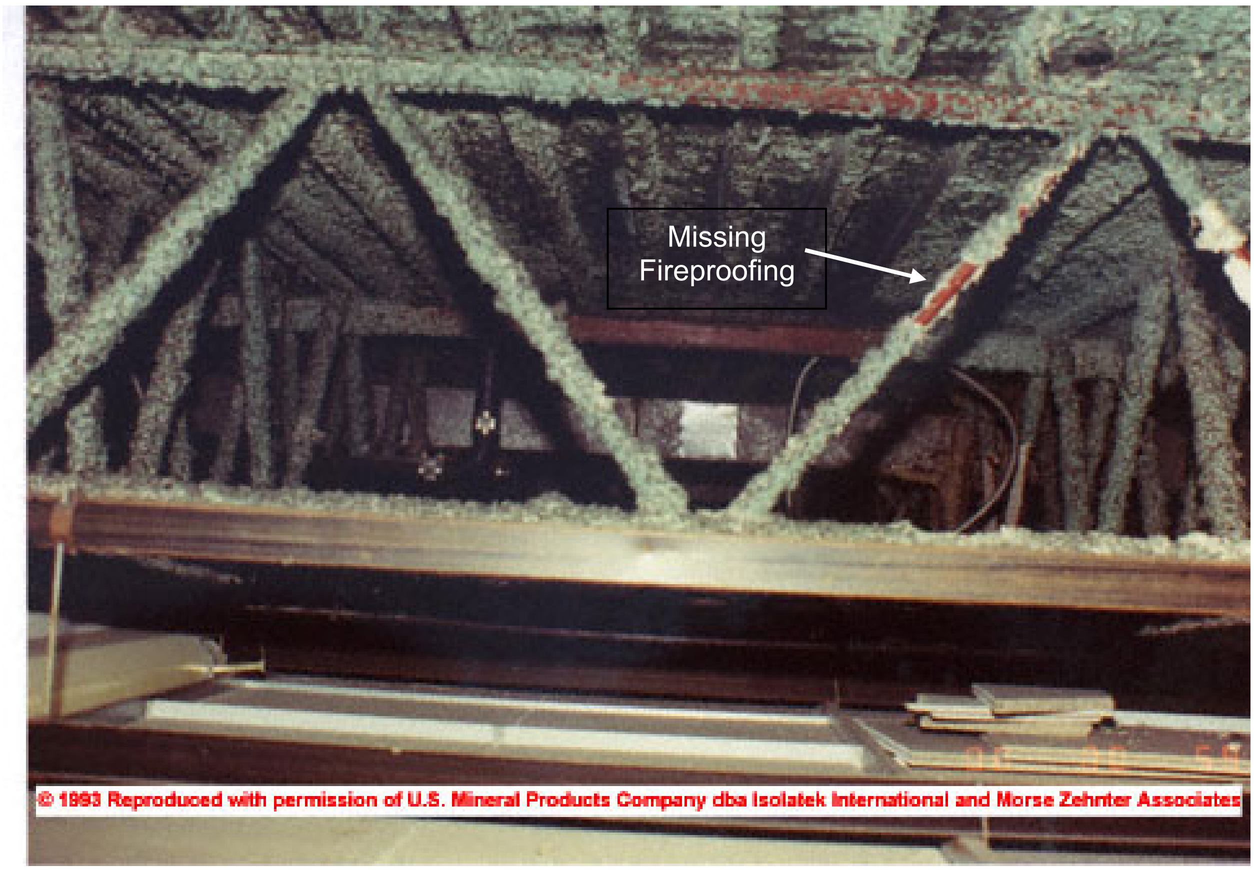


Figure I–4. Example of "gap" in fireproofing on diagonal member of a bridging floor truss.

The combined effects of variation in thickness of the fireproofing and length of missing fireproofing were examined by a factorial study with the following factors:

- Average thickness of fireproofing varying from 0 in. to 2.0 in. in 1/4 in. increments;
- Standard deviation of fireproofing thickness of 0 in., 0.25 in., 0.5 in., 0.75 in. and 1.0 in.; and
- Length of missing fireproofing varying from 0 in. to 30 in., in 6 in. increments.

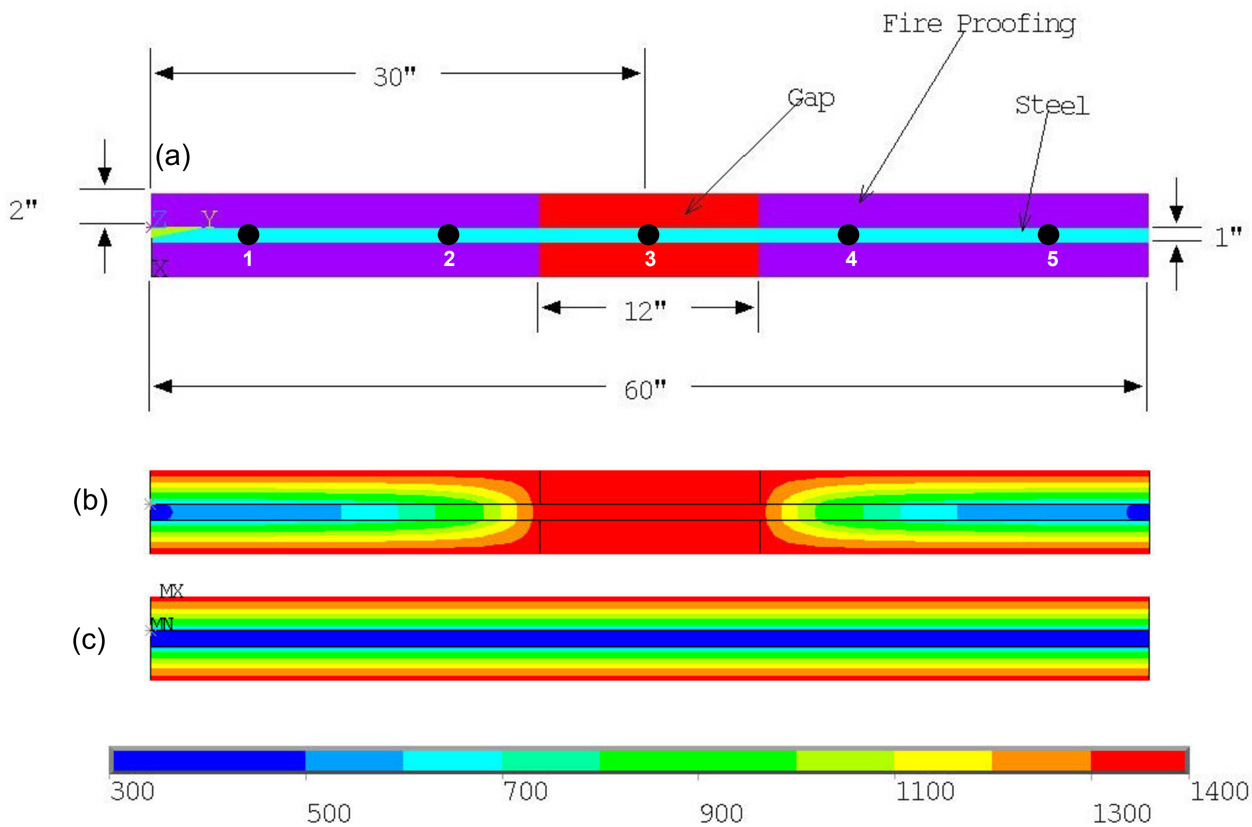


Figure I–5. Effects of gap in fireproofing: (a) model of plate with fireproofing having 2 in. uniform thickness and 12 in. gap, (b) isotherms (K) at time = 50 min with 12 in. gap, and (c) isotherms without gap.

The results of the sensitivity study can be summarized in a series of plot matrices, which show the time histories of the steel temperature for different combinations of gap length and variability in fireproofing thickness. For example, Fig. I–6 shows the plot matrix for the temperature history at point #2 (18 in. from the end of the plate). Each plot contains a series of curves representing different average thickness of fireproofing, as in Fig. I–3. Each column of plots represents a constant value of thickness variability (standard deviation), and each row represents a constant gap length. The plot in the upper left corner represents the case of uniform thickness of fireproofing and no gap, which is the same plot as in Fig. I–3(a). (Note that for the case of uniform thickness and no gap, the steel temperature at any point in a cross section is the same along the length of the plate, as shown in Fig. I–5(c).) For gaps of 24 in. and 30 in., the temperature at point #2 rises rapidly because there is no fireproofing on the plate at that location. This explains the shapes of the curves in the two lower rows. In going from left to right in one of the top four rows it is seen that as variability of thickness increases, the time histories shift upward, thereby reducing the time to reach 600°C. This is the same observation as shown in Fig. I–3. Moving from the top to the bottom in any column shows the effects of increasing gap length. The effect of gap length depends, of course, on where the steel temperature is measured. At a point within the portion of steel that is bare, the temperature rises quickly. At points within the steel that are surrounded with fireproofing, the gap provides a path for heat flow, as shown in Fig. I–5 (b). As a result, points in the steel within the vicinity of the missing fireproofing will experience higher temperatures, as indicated by the rising trend of the curves in going downward from the top of a column in Fig. I–6. The National

Institute of Standards and Technology (NIST) does not have sufficient information to determine the frequency of occurrence of these gaps or their typical locations. Therefore, gaps in fireproofing will not be considered in the thermal modeling.

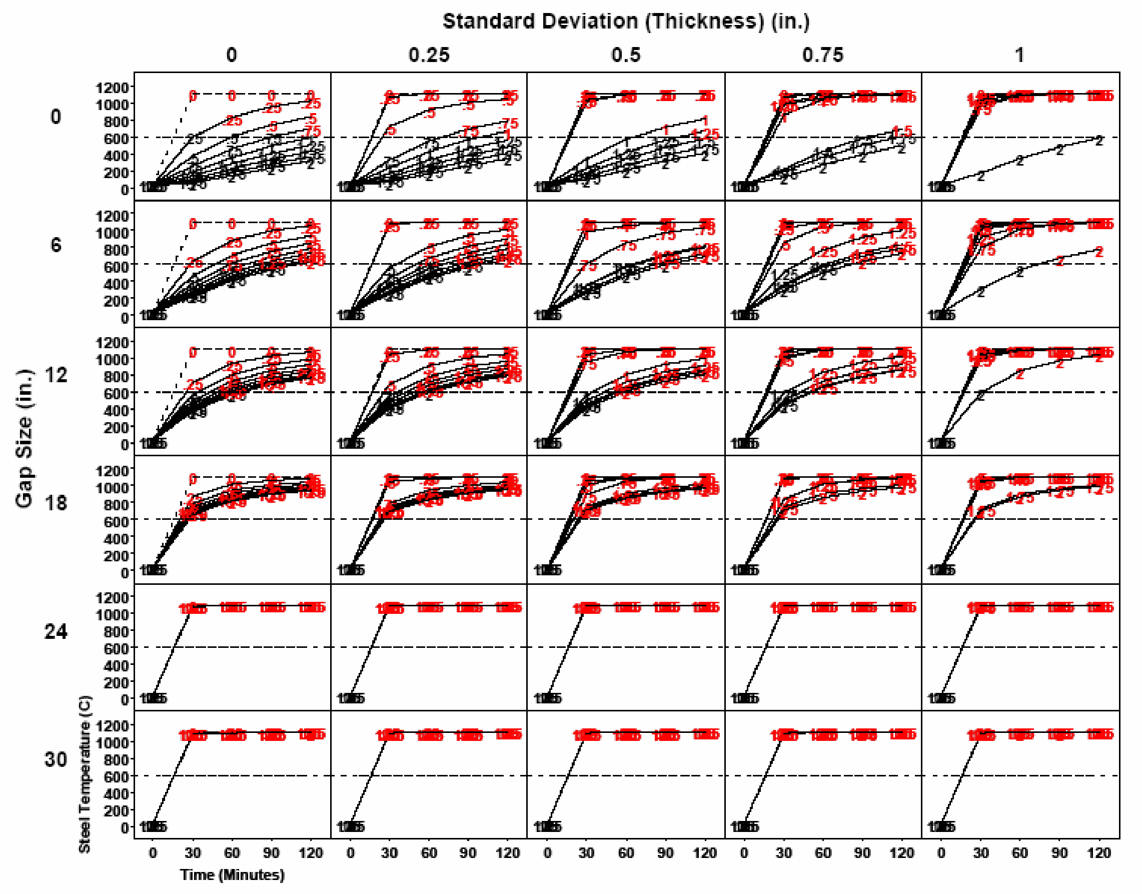


Figure I–6. Example of plot matrix from sensitivity study of the effects of missing fireproofing and variability of fireproofing thickness on steel temperature. Each graph is a temperature history of the steel at point #2 (see Fig. I–5) for different thicknesses of fireproofing.

I.3 IN-PLACE CONDITIONS OF FIREPROOFING BEFORE IMPACT

I.3.1 History of WTC Fireproofing

In Appendix 4 of the *May 2003 Progress Report* (NIST SP 1000-3), the history of the sprayed fireproofing, as reconstructed from available documentation, was reviewed. Basically, the following significant activities took place:

- 1969: Decision made to use 1/2 in. of CAFCO BLAZE-SHIELD Type D (asbestos fibers) sprayed fireproofing.

- 1970: Use of CAFCO BLAZE-SHIELD Type D was discontinued at the 38th floor of WTC 1; remaining fireproofing to use CAFCO BLAZE-SHIELD Type DC/F (mineral wool fibers).
- 1994: Thickness measurements of fireproofing on trusses of floors 23 and 24 of WTC 1.
- 1995: Port Authority performed study to establish sprayed fireproofing thickness for tenant alterations.
- 1999: Port Authority established guidelines for fireproofing repairs, replacement, and upgrades.
- Late 1990s: Floor truss fire protection upgraded to 1 1/2 in. during tenant alterations using CAFCO BLAZE-SHIELD Type II. In-place measurements of thickness, density, and bond strength recorded.

I.3.2 Specified Thickness of Fireproofing

WTC project specifications for spray-applied fireproofing do not provide required material thickness or hourly ratings. However, a letter dated October 30, 1969, from Robert J. Linn (manager, Project Planning, WTC) to Mr. Louis DiBono (Mario & DiBono Plastering Co., Inc.) states, in part:

> …Tower "A" columns that are less than 14WF228 will require 2 3/16″ thick of 'Cafco [B]laze-Shield Type D' spray-on Fireproofing. All Tower columns equal to or greater than 14WF228 will require 1 3/16″ of fireproofing…
>
> All Tower beams, spandrels and bar joists requiring spray-on fireproofing are to have a 1/2″ covering of "Cafco."

No reference is made in this letter to the required thickness of fireproofing of core box columns or exterior built-up columns.

Alcoa was the supplier of the aluminum cladding on the exterior columns (Contract WTC 400.00), and the following "Note 11" was included among the "General Notes" of their drawings:

> 11. Exterior column and spandrel fireproofing–CAFCO BLAZE SHIELD Type D Fireproofing. Interior column and spandrel fireproofing–Vermiculite plaster aggregate fireproofing with finished plaster coat on exposed areas of columns. (3 hr on spandrels, 4 hr on columns)

	Fireproofing Thickness	
Rating	**Cafco**	**Vermiculite Aggregate**
4 hr (heavy column)	1 3/16″	7/8″
3 hr (spandrels)	1/2″	1/2″

In 1995, the Port Authority performed a study to establish the requirements for applying spray-on fireproofing to the floor trusses in the case of new construction (alterations conducted when tenants vacated the space) in the towers. The study estimated the fireproofing requirements for the floor trusses of the towers based on "the fireproofing requirements for Design No. G805 contained in the Fire Resistance Directory" of Underwriters' Laboratories. The study concluded that 1 1/2 in. of spray-on mineral fiber fireproofing, "when applied directly to the chords and web members," was sufficient to achieve the required 2 h rating for the floor trusses. In the years between 1995 and 2001, fireproofing was upgraded in a number of the floors affected by the fires on September 11, 2001.

The specified fire protection is summarized in Table I–1.

Table I–1. Specified passive fire protection.

Structural Component	Member Size	Location	Material	Thickness (in.)
Floor trusses	All	NA	CAFCO DC/F	1/2
Interior columns[a]	< 14WF228	NA	CAFCO DC/F	2 3/16
	≥ 14WF228	NA	CAFCO DC/F	1 3/16
Exterior columns	"heavy"	Exterior faces	CAFCO DC/F	1 3/16
	"heavy"	Interior faces	Vermiculite aggregate	7/8
Spandrel beams	All	Exterior face	CAFCO DC/F	1/2
	All	Interior face	Vermiculite aggregate	1/2

a. No thicknesses specified for core beams and box columns.
Key: NA, not applicable.

In a letter dated July 25, 1966, from Emery Roth and Sons to the Port of New York Authority, it is stated "Since the deck is non-structural it will not be fire proofed." Photographs show that in some areas the underside of the metal deck was indeed not fireproofed, while in other areas fireproofing appears to be present but of undetermined thickness and possibly resulting from overspray. Photographs reveal that the dampers and damper saddles were not fireproofed. Additionally, it is unclear whether the bridging trusses were required to be fireproofed in all areas. Subsequent to the design and construction of the WTC towers, some information has been found that further describes the elements of the structural systems that were indeed fireproofed.

I.3.3 As-Applied Thickness and Variability

The actual thickness of a spray-applied fire protection material generally exceeds the specified thickness by some amount. Since both towers collapsed on September 11, 2001, and most of the fireproofing was either dislodged or abraded (or scraped) off in the collapse, no examples remain of the "as installed" condition of the fireproofing. To make an estimate of the as-applied thickness and variability in thickness, several sources of information have been employed, including measurements taken by the Port Authority, condition surveys and anecdotal information, and photographs and video clips showing the condition of the fireproofing in selected areas. Each of the structural components or systems is considered here separately.

Steel Truss-Supported Floor System

Qualitative information on the "as installed" fireproofing thickness for the floor system first appears in Sample Area Data Sheets from 1990, in which comments on the state of the in-place fireproofing were recorded. As an example, the data sheet for floor 29 of WTC 1 states the following for the South West quadrant of the floor:

> Fluffy spray-on fireproofing coating the support beams, joists, and deck above the ceiling. The thickness of the material on the beams and joists was consistently about 1/2″ Regarding the deck it ranged from very sparce [sic] in areas to 1/4″ other areas.

Similar statements were recorded for the remaining quadrants of the floor.

Information regarding quantitative inspection of existing fireproofing appears in documentation from 1994. That year, the Port Authority performed a series of thickness measurements of the existing fireproofing on floors 23 and 24 of WTC 1. Six measurements were taken from "both flanges and web" of each of 16 randomly chosen trusses on each floor at those locations where the fireproofing was not damaged or absent.

The averages of six measurements per joist that were recorded on the two floors are presented in Table I–2. Measured average thickness varied between 0.52 in. and 1.17 in. For the 32 measurements (16 on each floor), the overall average was 0.74 in. and the standard deviation of these averages was 0.16 in. Four of the 32 floor trusses, had an average thicknesses between 0.52 in. and 0.56 in. These measurements suggest that the minimum average thickness exceeded 1/2 in.

This same report stated that, on floor 23,

> ... truss members located adjacent to the outside walls (within 3 ft) are devoid of fireproofing material. Visual inspection on floor 24 was not possible, as this area still has a lowered ceiling in place.

The data in Table I–2 can be examined further to understand the variability of the fireproofing thickness in the non-upgraded locations. Figure I–7 (a) shows the average thicknesses measured on the floor trusses of floors 23 and 24. The values appear to be similar for the two locations in terms of overall average thicknesses and the variation in average thickness. A formal analysis of variance indeed indicated no statistically significant differences between the overall mean thicknesses for the two floors. Thus, the two groups of data can be combined into one. A question to be answered is whether the values of average thickness follow a normal distribution. To answer this question, histograms and normal probability plots are used. Figure I–7 (b) shows a histogram of the average thicknesses, and it appears to be non-symmetrical and skewed to the right, which is characteristic of a lognormal distribution.[1] Figure I–7(c) is the normal probability plot of the average thicknesses for the combined data. If the points fall approximately on a straight line, it indicates that the data are normally distributed. It is seen that there are systematic deviations of the data from the best-fit line. To examine whether the data are represented better by a lognormal distribution, the average thicknesses, in Table I–2 were transformed by taking their

[1] In a lognormal distribution, the natural logarithms of the values of a variate have a normal distribution.

natural logarithm. Figure I–7 (d) is a histogram of the natural logarithms of thickness, and Fig. I–7(e) is the corresponding normal probability plot. It is seen that the data are less dispersed about the straighter line, and the correlation coefficient has increased form 0.97 to 0.99. Thus, there is some indication that the distribution of fireproofing thickness is lognormal in the non-upgraded floor trusses.

Table I–2. Average fireproofing thickness from six measurements taken in 1994 on each of 16 random floor trusses on floors 23 and 24 of WTC 1.

Fireproofing Thickness (in.)	
Floor 23	**Floor 24**
0.60	0.76
0.53	0.60
0.70	0.90
0.76	0.72
0.88	0.64
0.89	0.80
0.83	0.68
1.17	0.65
0.88	0.67
0.71	0.77
0.82	0.96
0.52	0.66
0.69	0.65
0.52	1.11
0.64	0.95
0.52	0.56

Source: Data provided by Port Authority of New York and New Jersey.

A lognormal distribution for the average thickness of the fireproofing on the non-upgraded floor trusses is explained as follows. It is expected that the thickness of fireproofing will be highly variable due to the difficulty in spraying the material on the relatively thin members. If the overall thickness is low and the variability is high, a normal distribution would require a fraction of the surfaces to have negative values of fireproofing. If the thickness distribution is lognormal, the thickness cannot be zero, and there is a low likelihood of having thickness close to zero. If the underlying distribution of fireproofing thickness is lognormal, the average thickness overestimates the thickness expected to be exceeded with 50 percent probability, and the median is the appropriate statistic for the 50 percentile value.

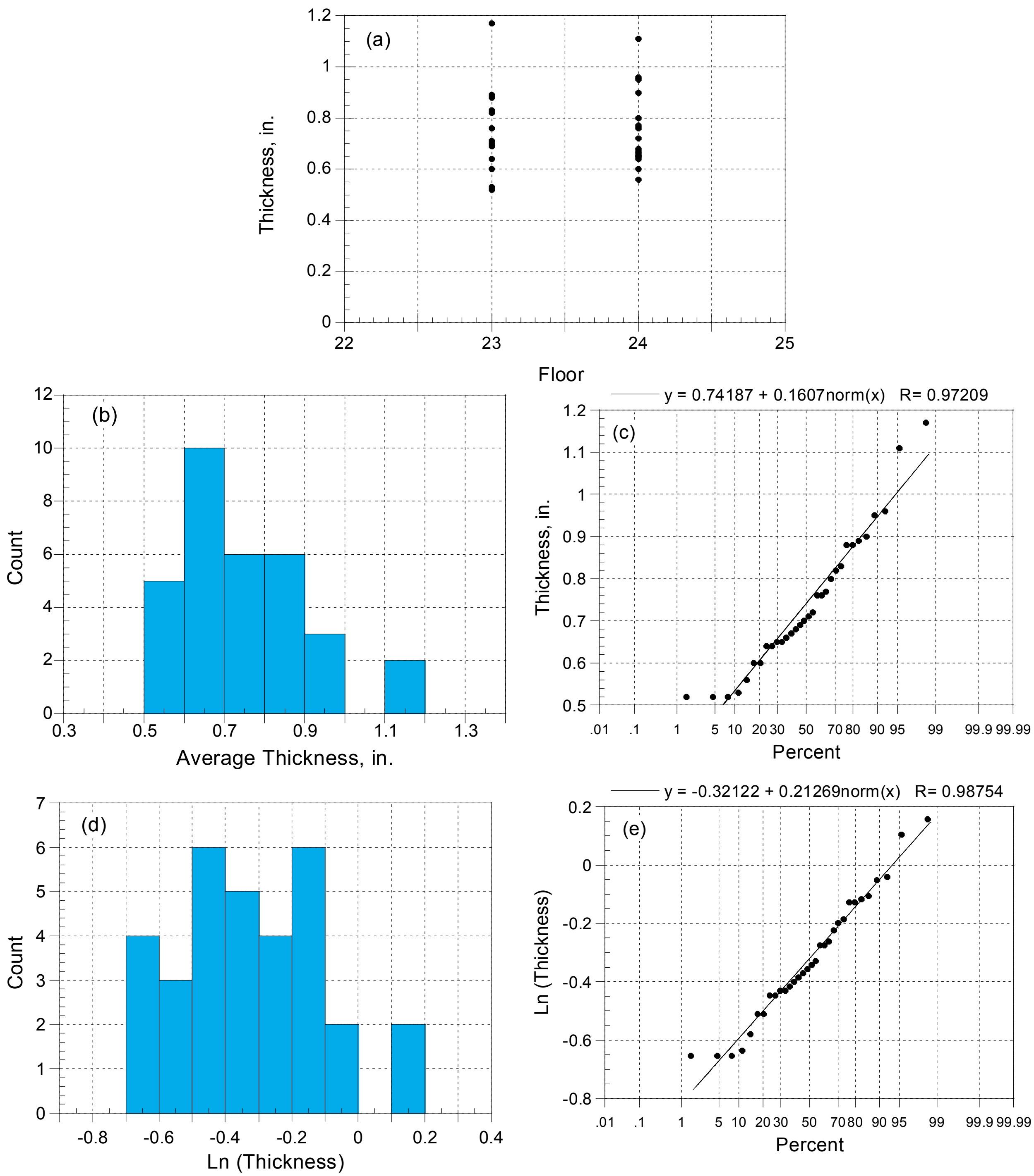


Figure I–7. (a) Dotplot of average thickness from floor trusses for floors 23 and 24, (b) histogram of average thickness, (c) normal probability plot of average thickness, (d) histogram of natural logarithm of average thickness, and (e) probability plot of natural logarithm of average thickness.

As stated, the standard deviation of the average thicknesses in Table I–2 is 0.16 in. Since each of the averages is based on six individual measurements, the variability in average thickness is less than the variability of the fireproofing thickness on a given element. If it is assumed that the true average thicknesses of fireproofing at the truss locations represented in Table I–2 are the same, it is possible to estimate the variability of individual measurements from the following well-known relationship:

$$S_{\overline{X}} = \frac{S}{\sqrt{n}} \tag{I.1}$$

where:

$S_{\overline{X}}$ = standard deviation of the average thicknesses

S = standard deviation of the individual thickness measurements

n = number of measurements to obtain the average thickness

Thus, an estimate of the standard deviation of the individual measurements is $0.16\sqrt{6} \approx 0.4$ in. Since it is unlikely that there is no difference in average fireproofing thickness at different cross sections, the standard deviation of 0.4 in. is an upper limit for the variability of fireproofing thicknesses in the non-upgraded floor trusses on the basis of the information provide in Table I–2.

Analysis of Photographs

Additional data regarding the thickness of fireproofing has been gathered by evaluating photographic evidence. Although photographic evidence of the state of the fireproofing is limited, two groups of photographs have been located and used for estimating fireproofing thickness.

The first group of photographs was provided to NIST by Morse Zehnter Associates and includes images of floor trusses from WTC 1 (floors 12, 22, 23, and 27) and WTC 2 (floor 26). From this group, only photographs from floors 22, 23, and 27 of WTC 1 were analyzed. Photographs provided by Morse Zehnter Associates were taken in the mid-1990s and illustrate the fireproofing conditions prior to the upgrade carried out by the Port Authority. Thus, fireproofing thickness on the photographed trusses should be at least 1/2 in. as specified by the Port Authority on October 1969.

The second group of photographs, taken in 1998, was provided by Gilsanz Murray Steficek (consulting engineers). This group illustrates the state of fireproofing after the upgrade program that was initiated in 1995. The photographs were of trusses for floor 31 and below in WTC 1.

Selection of which photographed trusses were used to estimate thickness of fireproofing was based on clarity of fireproofing edges and whether a feature of known dimensions was present. Thus, only photographs where reference measurements could be performed were used. The general approach to the analysis involved the estimation of distances based on the computed reference length per pixel. The procedure is summarized as follows:

- A feature of known dimension (based on construction drawings) that could be used as reference was located in the photograph. For example, the dimension of the bare vertical leg of a damper saddle was a dimension that could be obtained from shop drawings.

- In the photograph, the length of the reference dimension was measured in pixels.
- The scaling factor of length per pixel was computed by dividing the known dimension in inches by the number of pixels. For example, if the vertical leg of the damper saddle was measured as 48.2 pixels in the photograph, and it is known that the actual size of the leg was 3.13 in., the scaling factor would be 3.13 in./48.2 pixels = 0.065 in./pixel.
- Only truss webs or struts (diagonal bar at end of truss) located near and in the same plane as the reference object were selected for analysis. This selection was made to minimize error due to perspective.
- It was assumed that the fireproofing on web bars was applied evenly around the perimeter of the bar. Based on this assumption, a “virtual” centerline along the length of the bar was drawn in the photograph.
- Lines were drawn perpendicular to the “virtual” centerline. The number of pixels along the lines from the “virtual” centerline to the edge of the fireproofing was determined from the cursor positions indicated by the software. Measurements were made at regularly spaced intervals to avoid bias. Figure I–8 is an example of a series of measurements made on a strut.

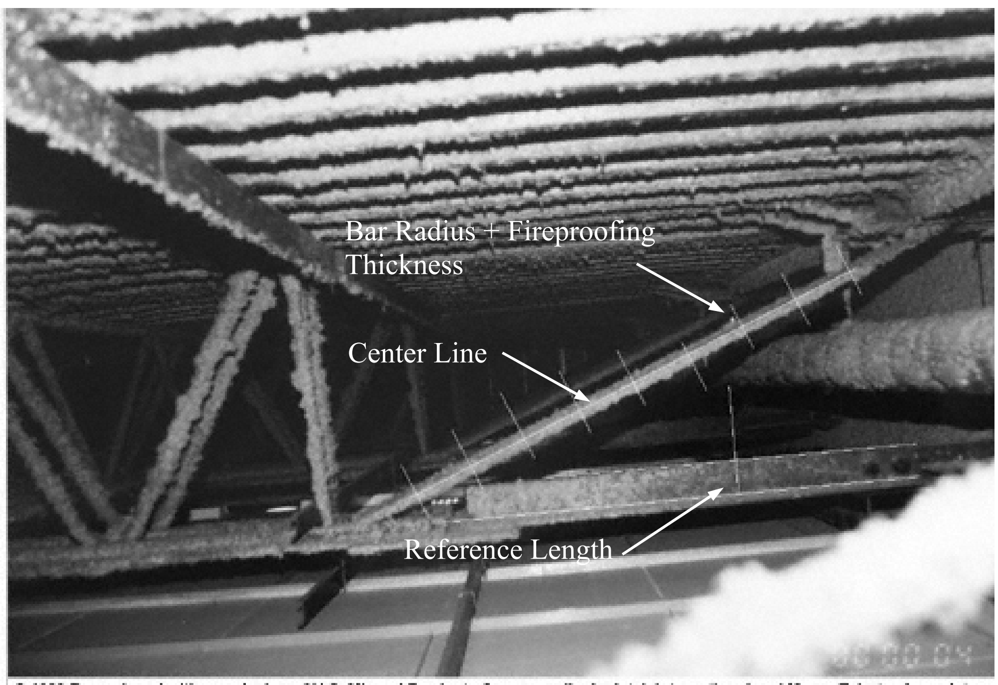


Figure I–8. Example of measurement procedure used to estimate fireproofing thickness from photographs.

- Each measurement in pixels was multiplied by the scaling factor (in./pixel) to estimate the bar radius plus fireproofing thickness.

- The radius of the bar was subtracted to provide the estimate of the fireproofing thickness.

It was observed that the estimated thickness of fireproofing in the non-upgraded floors tended to be larger for the webs of the main trusses. Hence estimates of fireproofing thickness were divided into three groups:

- Webs of main trusses,
- Webs of bridging trusses, and
- Diagonal strut at the exterior wall end of the truss.

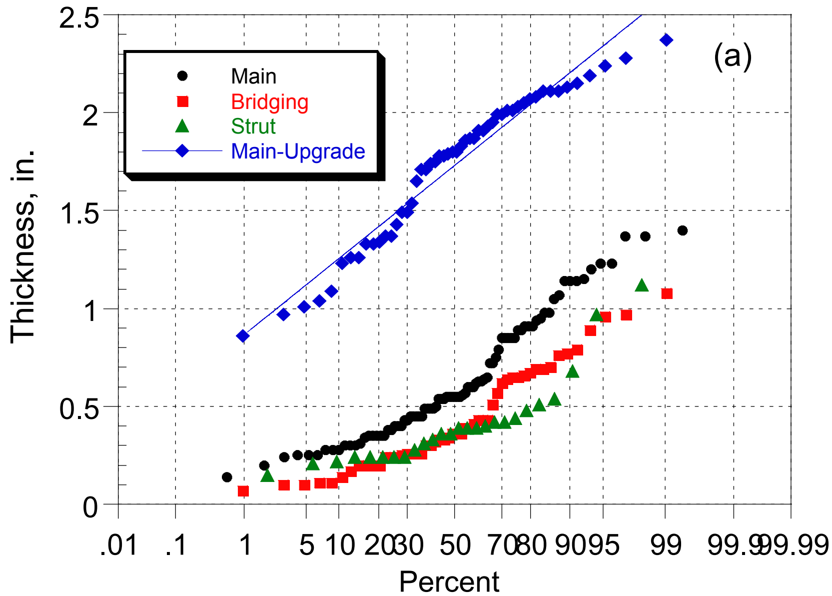
No estimates of fireproofing thickness on top and bottom chords were possible using photographs. For the upgraded floors in WTC 1 that were included in the second group of photographs, only estimates of the thickness on the web bars of the main trusses were made. Figure I–9 (a) shows normal probability plots of the fireproofing thickness estimated from the photographs. It is seen that the points for the "upgraded" main trusses follow a generally linear trend, which indicates that the estimated thicknesses for the upgraded main trusses are approximately normally distributed. The estimated thicknesses from the non-upgraded floors, however, do not follow linear trends on the normal probability plot. Figure I–9 (b) shows normal probability plots of the natural logarithms of the thicknesses. The transformed values for the non-upgraded fireproofing now follow generally linear trends, which means that a lognormal distribution is more appropriate for the non-upgraded floors. This reinforces the observation noted in the previous section. Thus there is strong evidence that the original fireproofing thickness on the floor trusses follows a log normal distribution.

The average, standard deviation, and coefficient of variation were computed for the total number of measurements in each of these groups. The results are summarized as follows:

- Main trusses before upgrade: Average thickness 0.6 in., standard deviation = 0.3 in., and coefficient of variation = 0.5.
- Bridging trusses before upgrade: Average thickness 0.4 in., standard deviation = 0.25 in., and coefficient of variation = 0.6.
- Diagonal struts before upgrade: Average thickness 0.4 in., standard deviation = 0.2 in., and coefficient of variation = 0.5.
- Main trusses after upgrade: Average thickness 1.7 in., standard deviation = 0.4 in., and coefficient of variation = 0.2.

Port Authority Data on Upgraded Fireproofing on Trusses

As discussed in the *May 2003 Progress Report* (NIST SP 1000-3), the Port Authority provided information on fireproofing thickness from tenant alteration Construction Audit Reports prepared in 1997 to 1999. Those reports included average thicknesses of fireproofing at the "bottom of truss." In 2004, the Port Authority provided NIST reports of the individual measurements for many of the average thicknesses in the Construction Audit Reports. With the individual measurements, it is possible to investigate the



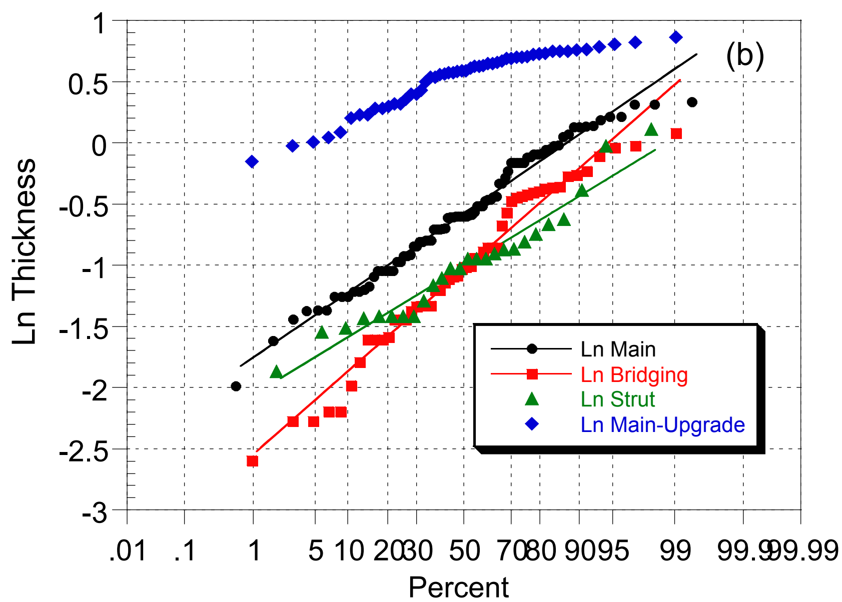


Figure I–9. (a) Normal probability plot of estimated fireproofing thickness based on photographs, and (b) normal probability plot of natural logarithms of thickness.

variation of thickness at a cross section of a truss member and the variation in average thickness from truss to truss. To permit such analyses, only those data having the same number of individual measurements at each cross section were used. This resulted in 18 data sets for WTC 1 (including floors 93, 95, 98, 99, and 100) and 14 data sets for WTC 2 (including floors 77, 78, 88, 89, and 92).

An analysis of the individual measurements was carried out to determine the underlying distribution for the measured thicknesses. Figure I–10 (a) is a dotplot of the individual measurements in WTC 1 (144 measurements) and in WTC 2 (112 measurements). It is observed that the central values and ranges are similar for the two towers, and the two groups of measurements were combined into one group. Figure I–10 (b) is the histogram of the individual measurements, and Fig. I–10 (c) is the corresponding normal probability plot. A straight line fit to the normal probability plot shows a tendency of the points to deviate from the line. Figure I–10 (d) is a histogram of the natural logarithms of the individual thickness values, and Fig. I–10 (e) is the corresponding lognormal probability plot. A comparison of the probability plots shows that natural logarithms fall closer to a straight line. Thus, it appears that the thickness of the upgraded fireproofing on the floor trusses is described by a lognormal distribution. This contradicts the observation based on analysis of photographs from lower floors discussed in the previous section. The overall average thickness of the 256 individual measurements is 2.5 in. with a standard deviation of 0.6 in. Thus, the average thickness on the upgraded upper floors appears to be greater than that estimated from photographs taken on upgraded lower floors.

The overall standard deviation of 0.6 in. includes two contributions: (1) the variation of thickness at the cross section (within-truss variability), and (2) the variation of average thickness between trusses (between-truss variability). Figure I–11 shows these two components of the thickness variability for the two towers. Figures I–11 (a) and (c) show the within-truss variability, and Figs. I–11 (b) and (d) show the variation of average thickness of each truss. From analysis of variance, it was found that the within-truss standard deviation is 0.4 in., and the between-truss standard deviation is also 0.4 in. The within-truss standard deviation of 0.4 in. is similar to the standard deviation of the estimated individual thickness obtained from analysis of the photographs of upgraded main trusses.

Column Fireproofing Thickness

NIST requested that the Port Authority provide available information on the thickness of fireproofing for the exterior and interior columns of the WTC towers. Specifically, the request included the following:

- The fireproofing material used and the thickness on the various plates comprising the exterior columns and spandrels.
- The fireproofing material used and the thickness on core columns.
- Confirmation that the wide flange column sections were protected with CAFCO BLAZESHIELD Type DC/F with specified thickness of 2 3/16 in. for sections smaller than 14WF228 and 1 3/16 in. for 14WF228 and larger.
- Information on in-place fireproofing thickness.

The Port Authority replied that, due to inaccessibility of exterior columns and core columns, there were no recent records of fireproofing thickness for these elements. The only available measurements of fireproofing thickness were for beams and columns accessible within elevator shafts. The most complete data set included measurements on beams and columns taken within shaft 14/15 in WTC 1. These measurements were taken in April 1999 and included measurements from floor 1 to floor 45. The thicknesses were recorded to the nearest 1/8 in., with a few thicknesses recorded to the nearest 1/16 in. The columns included 10 to 18 replicate measurements, and the beams included 11 to 16 replicate measurements.

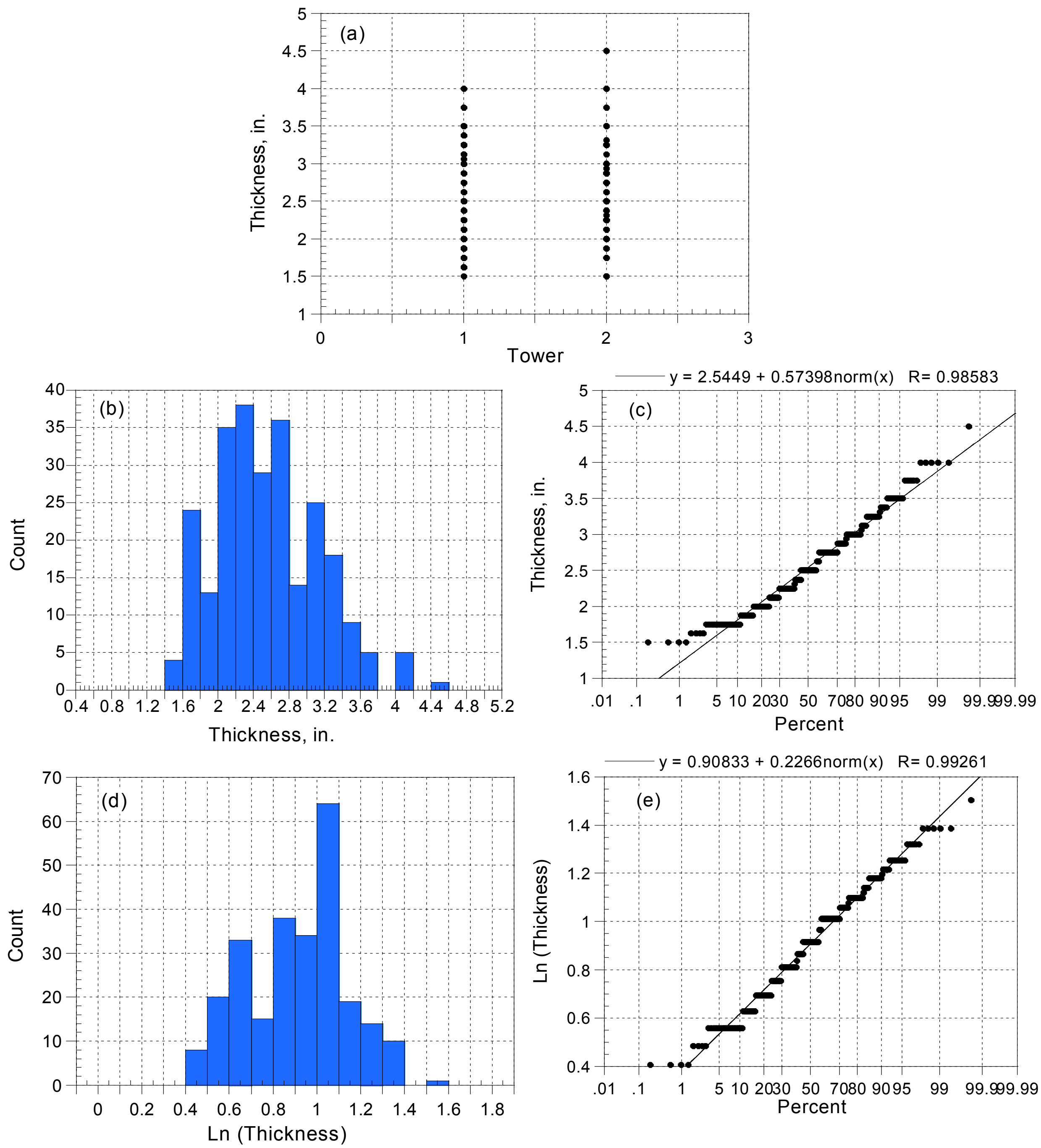


Figure I–10. (a) Dotplot of individual thickness measurements on floor trusses from Port Authority Construction Audit Reports, (b) histogram of thickness measurements, (c) normal probability plot of thickness measurements, (d) histogram of natural logarithms of thickness measurements, and (e) normal probability plot of natural logarithm of thickness measurements.

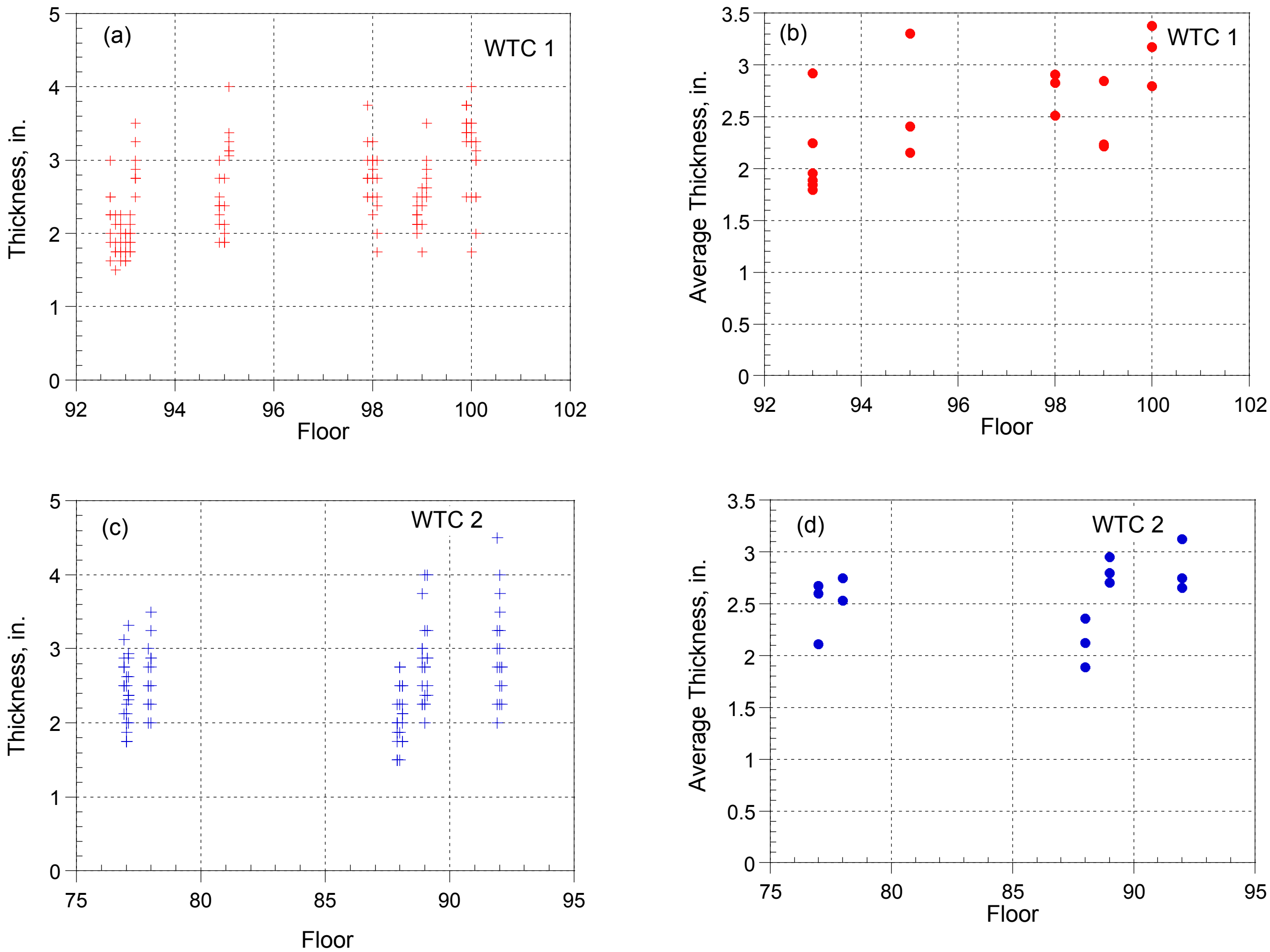


Figure I–11. Fireproofing thickness on floor trusses in upgraded portions of WTC towers: (a) individual measurements in WTC 1, (b) average thickness in WTC 1, (c) individual measurements in WTC 2, and (d) average thickness in WTC 2.

Figure I–12 (a) shows the individual and average fireproofing thickness on the core columns. Analysis of variance indicated no statistically significant differences among the average values and all data were pooled together. The average thickness for the columns is 0.82 in., the standard deviation is 0.20, and the coefficient of variation is 0.24. The information from the Port Authority indicated that the "minimum thickness required" for the columns was 0.5 in. Figure I–12 (b) is the normal probability plot of the individual thickness measurements. Because most of the thicknesses were reported to the nearest 1/8 in., the points are staggered instead of uniformly distributed. The plot, however, shows that the points follow a linear trend, and it appears that the thickness of the fireproofing on the core columns could be described by a normal distribution. Figures I–12 (c) and (d) shows the corresponding plots for the thickness of fireproofing on the beams. The average thickness for the beams is 0.97 in., the standard deviation is 0.21 in. and the coefficient of variation is 0.21. The information from the Port Authority indicated that the "minimum thickness required" for the beams was 0.75 in.

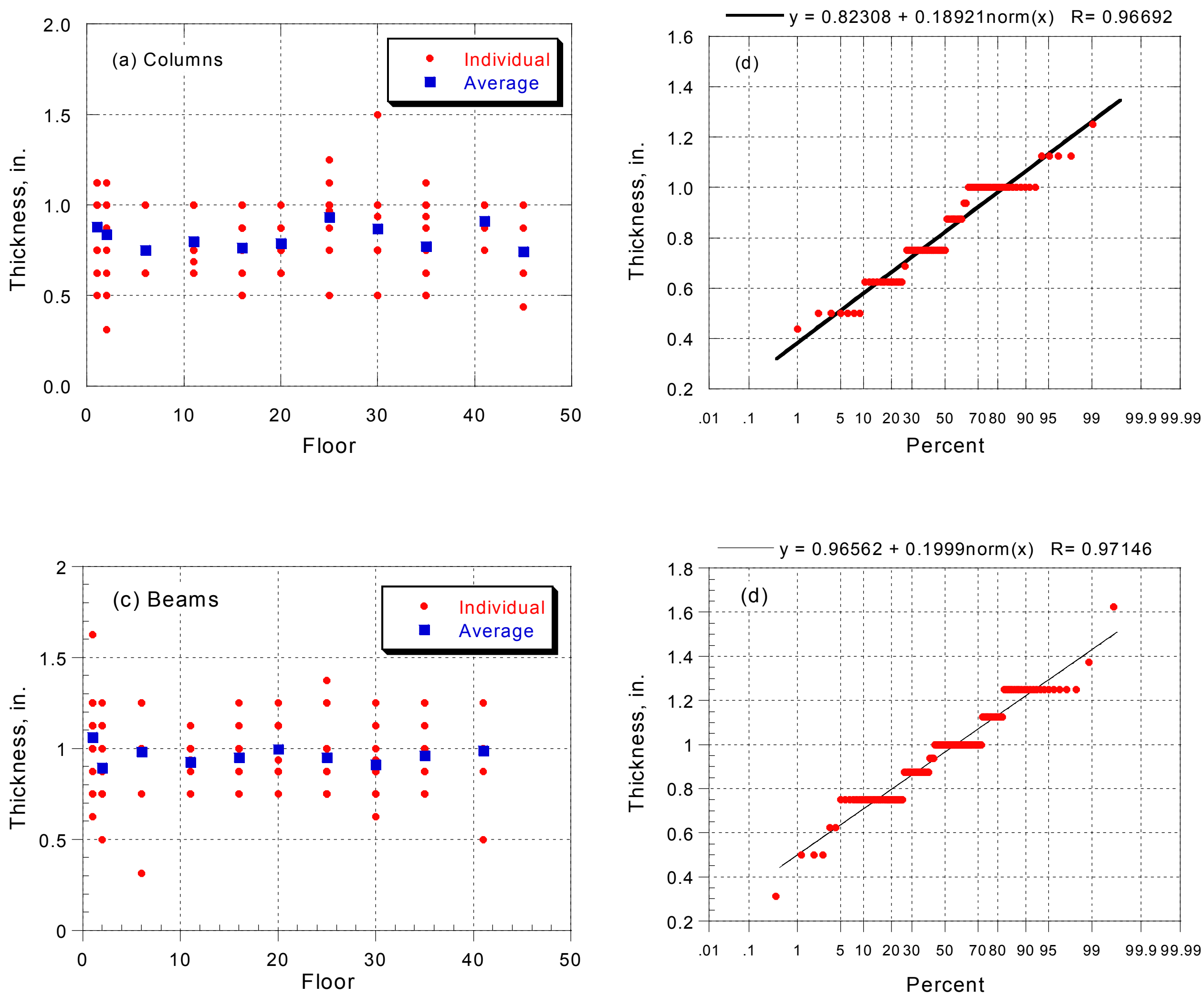


Figure I–12. (a) Individual and average thickness for core columns, (b) normal probability plot of individual measurements on columns, (c) individual and average thickness for core beams, and (d) normal probability plot of individual measurements on beams.

As might be expected, the variation in thickness of fireproofing for the beams and columns is lower than the variation observed in the floor trusses. The planar surfaces of the beams and columns result in more uniform application of the sprayed fireproofing than for the slender truss members. This results in reduced differences in the average thickness of fireproofing on different members and less variability within a member.

I.3.4 Equivalent Thickness

The sensitivity study summarized in Section I.2 indicated that variation in the thickness of fireproofing reduced the "effective thickness" of the fireproofing. It would be impractical to attempt to account for the variation in fireproofing thickness in the thermal modeling by introducing variable thickness fireproofing in the finite-element models. As an alternative, it was decided to attempt to determine the "equivalent uniform thickness" of fireproofing that would result in the same thermo-mechanical response of a member as variable thickness fireproofing. An approach similar to the methodology described in Section I.2 was used to model a 1 in. diameter by 60 in. long bar with fireproofing and subjected to the heat flux arising from a 1,100 °C fire. The bar was subdivided into 0.6 in. long elements, so that there were 100 elements along the length of the bar. The thermal history of the bar was calculated, and that history was used to calculate the length change of the unrestrained bar under a tensile stress of 12,500 psi. The bar was assumed to be similar to the steel used in the floor trusses, and the temperature dependence of the coefficient of thermal expansion and the modulus of elasticity were based on NIST measurements.

The fireproofing thickness in the models was based on the measurements summarized in the previous section for the web bars of main trusses in the original condition and after the upgrade. Specifically, the following target values were investigated:

- Original: average thickness = 0.75 in., standard deviation = 0.3 in., lognormal distribution.
- Upgrade: average thickness = 2.5 in., standard deviation = 0.6 in., lognormal distribution.

The variation of fireproofing thickness along the length of the bar was established by using a psuedo random number generator to select values from a lognormal distribution with central value and dispersion consistent with the above average values and standard deviation. Three sets of random data were generated for each condition.

When the randomly selected thicknesses of each element were applied to the bar, it resulted in sudden changes in fireproofing thickness along the length of the bar. This resulted in a “rough” surface texture as shown by the dotted thickness profile in Fig. I–13 (a). It was felt that this rough texture (see also Fig. I–1 (c) might not be representative of actual conditions, so an alternative approach was to use 5-point averaging to reduce the roughness of the fireproofing profile. The solid line in Fig. I–13 (b) shows such a “smooth” profile. The two profiles in Fig. I–13 (a) have approximately the same average value and standard deviation and have similar cumulative distribution of fireproofing thickness as shown in Fig. I–13 (b).

As stated, the calculated thermal histories of the bar elements were used to calculate the unrestrained length change of the bar due to thermal expansion and an applied stress of 12,500 psi. Work is currently underway to examine the performance of the bar under fully restrained conditions in which the induced stress history is computed. For comparison, the deformation of the bar with different but uniform thickness of fireproofing was calculated. The “equivalent thickness” was taken as the uniform thickness that resulted in similar deformation as under the variable thickness conditions. Figure I–13 (c) shows the results of these calculations for the original fireproofing. The three continuous curves are the deformation-time relationships for uniform thickness of 0.4 in., 0.5 in., and 0.6 in. The solid symbols represent the results for three cases with “rough” texture, and the open symbols are for the “smooth” texture. The following values summarize the six variable thickness profiles:

- Rough 1: average = 0.79 in., standard deviation = 0.29 in.
- Rough 2: average = 0.77 in., standard deviation = 0.27 in.
- Rough 3: average = 0.79 in., standard deviation = 0.31 in.

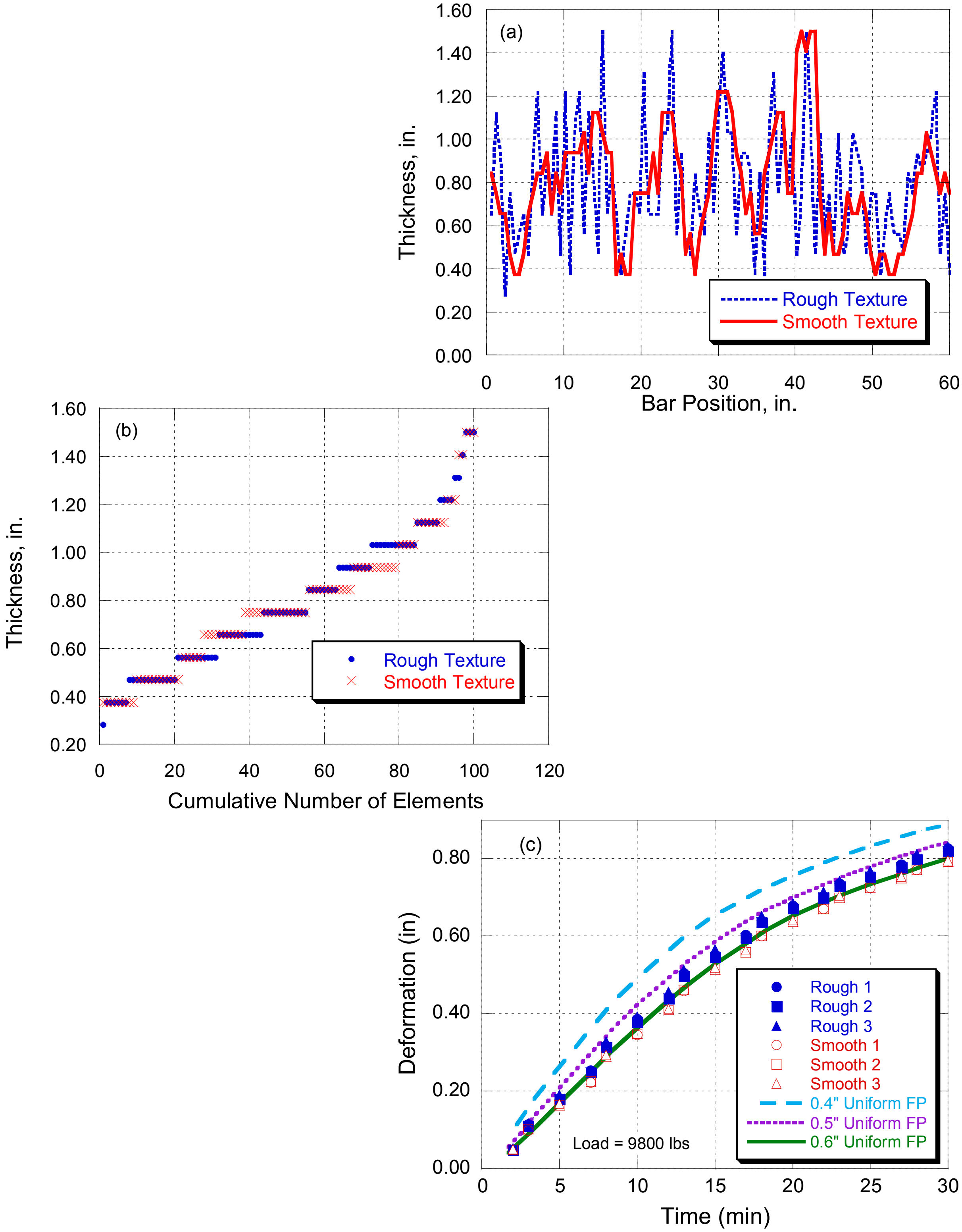


Figure I–13. (a) Randomly generated thickness profiles with average thickness of 0.75 in. and standard deviation of 0.3 in., (b) cumulative element size, and (c) deformation of 1 in. bar compared with deformation for uniform thickness of fireproofing.

- Smooth 1: average = 0.79 in., standard deviation = 0.28 in.
- Smooth 2: average = 0.78 in., standard deviation = 0.31 in.
- Smooth 3: average = 0.78 in., standard deviation = 0.32 in.

Figure I–13 (c) shows that the "rough" texture reduces the effectiveness of the fireproofing by a small amount compared with the "smooth" texture. As noted above, it is believed that the "smooth" texture is more representative of the actual conditions. On the basis of these analyses, it is concluded that fireproofing with an average thickness of 0.75 in. and a standard deviation of 0.3 in. provides equivalent protection to 0.6 in. of uniform thickness.

The results for the upgraded fireproofing are shown in Fig. I–14. Only the "smooth" texture was used, and the values for the three cases are as follows:

- Case 1: average = 2.50 in., standard deviation = 0.71 in.
- Case 2: average = 2.43 in., standard deviation = 0.51 in.
- Case 3: average = 2.55 in., standard deviation = 0.63 in.

Figure I–14 (a) shows the three profiles, and Fig. I–14 (b) shows the normal probability plots of thickness values. Because the three randomly generated profiles do not have the same averages and dispersions, the responses show more scatter than in Fig. I–13 (c). On the basis of these analyses, it is concluded that an average thickness of fireproofing of 2.5 in. with a standard deviation of 0.6 in. is equivalent to 2.2 in. of uniform thickness.

I.3.5 Thickness of SFRM for Use in Analyses

Analyses of available data on fireproofing thickness and thermal modeling revealed the following:

- From measurements of fireproofing thickness, the average values exceeded the specified thickness.
- Fireproofing thickness was variable, and the distribution of thickness in the floor trusses appears to be described best by a lognormal distribution.
- The standard deviation of fireproofing thickness on the trusses varied between about 0.3 in. to 0.6 in.
- The standard deviation of fireproofing on columns and beams from the core tended to be lower, with a value of 0.2 in. for the available data.
- No information is available on the fireproofing thickness on the exterior columns and spandrel beams.
- Variation in thickness reduces the effectiveness of fireproofing, and the equivalent uniform thickness is less than the average thickness.

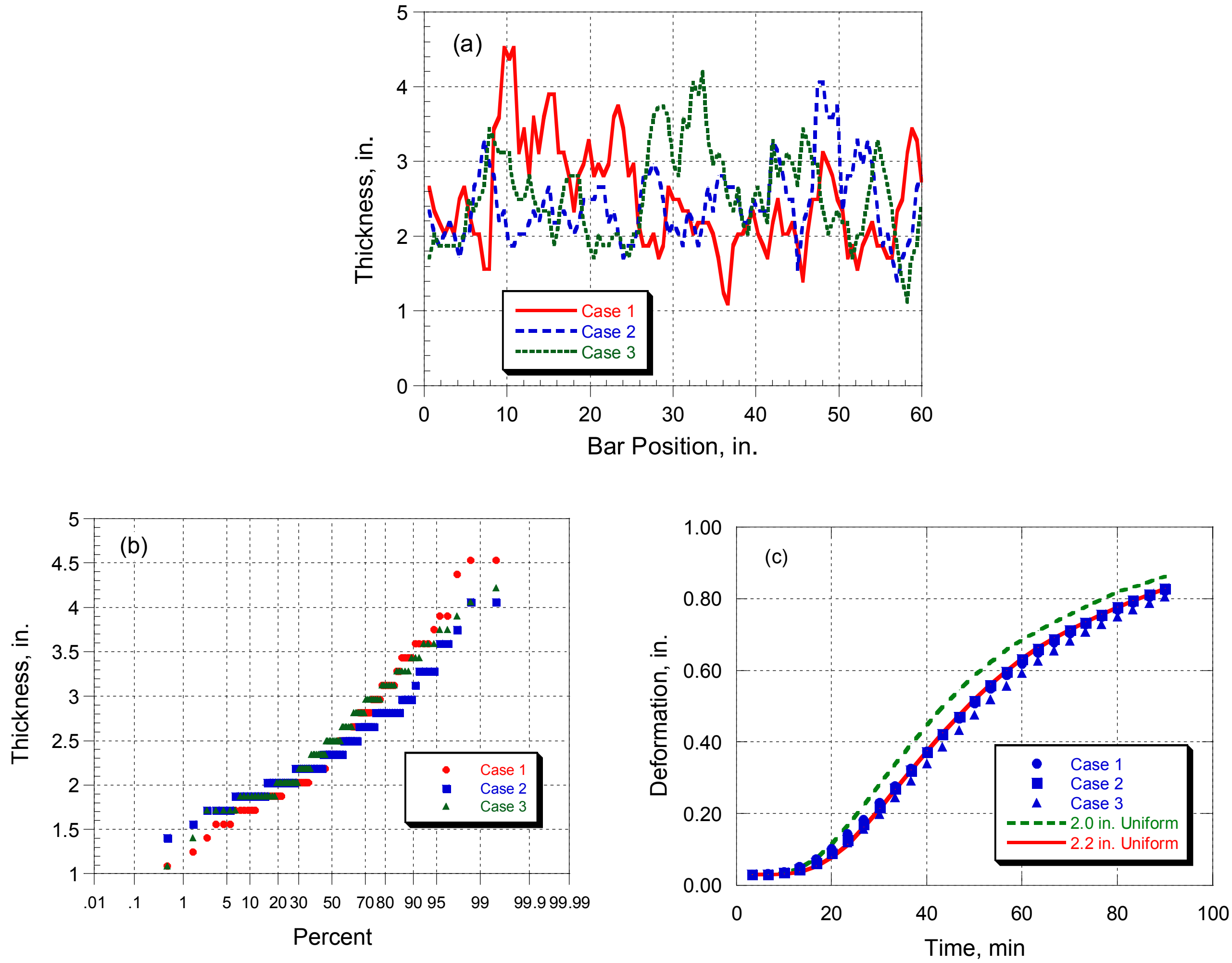


Figure I–14. (a) Randomly generated thickness profiles with average thickness of 2.5 in. and standard deviation of 0.6 in., (b) normal probability plots of thickness values, and (c) deformation of 1 in. bar compared with deformation for uniform thickness of fireproofing.

Based on the above findings, the following uniform thickness for the undamaged fireproofing will be used in calculating thermal response under various fire scenarios:

- Original fireproofing on floor trusses: 0.6 in.
- Upgraded fireproofing on floor trusses: 2.2 in.
- Fireproofing on other elements: the specified thickness.

The choice of specified thickness for those members lacking data is justified by offsetting factors as follows: (1) measured average thicknesses exceed specified values, and (2) variation in thickness reduces the effectiveness of fireproofing.

I.4 THERMAL PROPERTIES

Based on the information provided by the manufacturers, three SFRMs have been identified in WTC 1, 2, and 7: (1) CAFCO BLAZE-SHIELD Type DC/F, (2) CAFCO BLAZE-SHIELD Type II, and (3) Monokote MK-5. Of the three SFRMs, only CAFCO BLAZE-SHIELD Type II is currently sold in the U.S., and CAFCO BLAZE-SHIELD Type DC/F is sold in Canada.

CAFCO BLAZE-SHIELD Type DC/F is manufactured by Isolatek International (Stanhope, New Jersey) and was used in the interior columns, floor systems, and the exterior faces of the exterior columns of WTC 1 and WTC 2. CAFCO BLAZE-SHIELD Type II, also from Isolatek, was used in subsequent retrofit of WTC 1 floor systems. CAFCO BLAZE-SHIELD Type DC/F and Type II are portland cement-based products. Monokote MK-5 a gypsum-based SFRM, was manufactured by W.R. Grace and Co. (Cambridge, Massachusetts) and used in WTC 7. W.R. Grace stopped the production of Monokote MK-5 in the 1980s. In addition to these three SFRMs, vermiculite plasters, manufactured by W.R. Grace until the 1970s, were used on the interior faces of the exterior columns of WTC 1 and WTC 2.

To provide thermophysical property data for the modeling effort in fire-structure interaction, the thermal conductivity, specific heat and density of each SFRM were determined as a function of temperature up to 1200 °C. Tests were performed by Anter Laboratories, Inc. in Pittsburgh, PA through an open-bid contract. Anter Laboratories is an ISO 9002 certified company.

Samples of CAFCO BLAZE-SHIELD Type DC/F and Type II were prepared by Isolatek, Inc. in Stanhope, New Jersey, and sample of Monokote MK-5 were prepared by W.R. Grace and Co. in Cambridge, Massachusetts according to their respective application manuals. Since Monokote MK-5 is no longer on the market, it was specially manufactured by W.R. Grace according to the original MK-5 formulation. The samples were made from the same batch of raw material, shipped to NIST for examination and documentation, and sent to Anter Laboratories for testing. The sample is 9 in. long, 4.5 in. wide, and 3 in. thick. Three samples of each material were sent for testing. Two of them were used for the thermal conductivity measurements, and the third was used to prepare specimens for the other measurements involved.

I.4.1 Thermal Conductivity Measurements

The thermal conductivity measurements were performed according to ASTM C 1113 Test Method for Thermal Conductivity of Refractories by Hot Wire (Platinum Resistance Thermometer Technique). This test method is based on heating two specimens with a platinum wire placed between them. The thin platinum wire serves not only as a heater, but also as a temperature sensor, since the variation of its electrical resistance during the test is converted into variation of temperature. Thermal conductivity is calculated based on the rate of temperature increase of the wire and power input. It was reported that substantial shrinkage during the measurements occurred for the three materials. The two MK-5 specimens shrunk, exposing the platinum wire positioned between them. For this reason, no thermal conductivity measurement could be performed for this material at 1,200 °C. Figure I–15 (a) shows preliminary results for thermal conductivity as a function of temperature. The results show similar trends of increased thermal conductivity with increasing temperature; however, the Monokote MK-5 specimens had a different behavior than CAFCO BLAZE-SHIELD Type DC/F and Type II at temperatures above 500 °C.

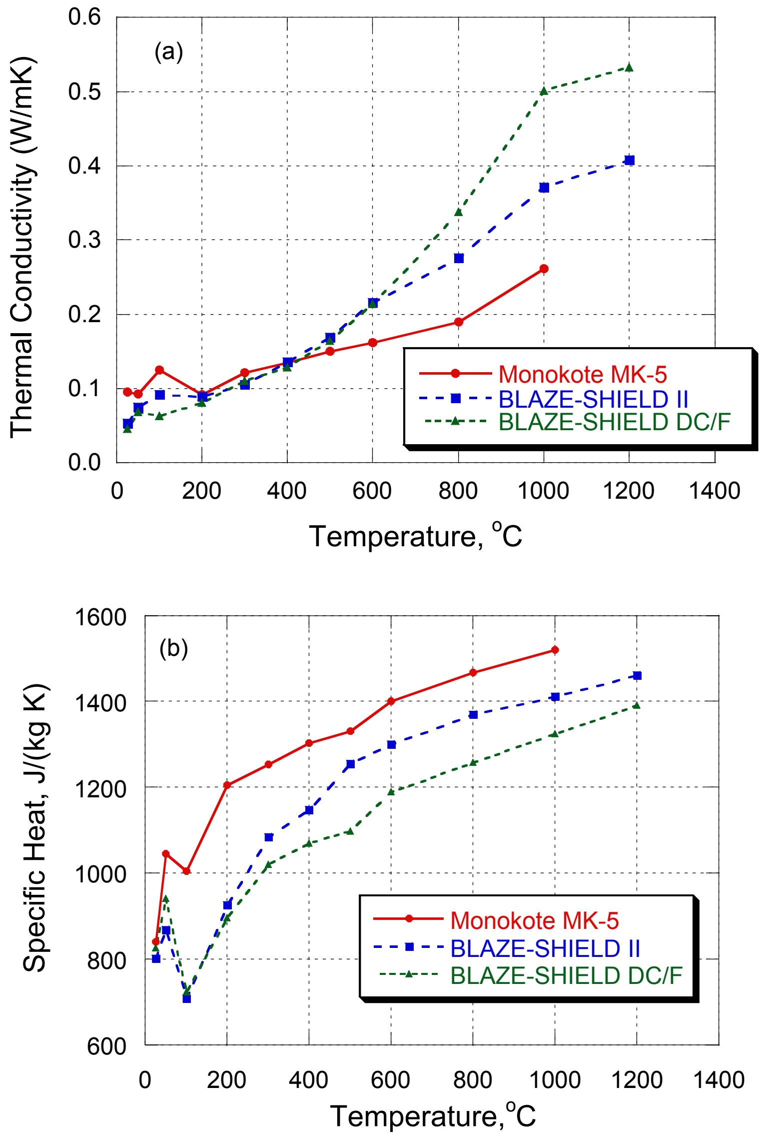


Figure I–15. Preliminary test results: (a) thermal conductivity as a function of temperature, and (b) specific heat as a function of temperature.

I.4.2 Specific Heat Measurements

For the specific heat capacity measurements, the same instrument (Unitherm Model QL-3141) was used with a slight modification. A thermocouple was added to the system and mounted on the specimen, parallel with the platinum wire at a known distance from the thermocouple. The test was performed in a similar manner as the thermal conductivity measurements, but from the thermocouple output the thermal diffusivity of the material was derived. Knowing the thermal conductivity, the thermal diffusivity, and the density calculated from the thermal expansion results and the thermogravimetric analysis, the specific heat of the material was calculated. Figure I–15 (b) shows preliminary results for specific heat as a function of temperature. It is seen that the materials had similar increasing trends with temperature, but the actual values differed.

I.4.3 Density Measurements

Densities of the samples were not measured directly (except at room temperature) but were calculated from TGA (thermal gravimetric analysis) and thermal expansion measurements. The TGA tests were performed according to ASTM Test Method E1131 using an Orton Model ST-736 TGA instrument. The thermal expansion tests were performed according to ASTM Test Method E228 using a Unitherm Model 1161 instrument. Since the materials were not isotropic, separate tests were performed for the X and Z orientations. It was assumed that the X and Y directions had the same thermal expansion. The Z direction was defined as the direction perpendicular to the fibrous strands in the specimens. The specimens were tested from room temperature to 1,200 °C at a heating rate of 2 °C/min. All of the specimens shrank during the tests and, in all cases, lost contact with the pushrod before reaching the maximum test temperature.

From the thermal expansion test results, the change in volume for each material was calculated at each temperature of interest. The density values were calculated from the results of the TGA and thermal expansion.

I.5 RESPONSE TO IMPACT

In order to estimate the extent of damage or loss of SFRM due to aircraft impact, the detailed finite element analysis of aircraft impact into the WTC towers, conducted within the framework of Project 2 of the investigation, will provide the following information:

***Debris Field*—**A database and graphics of the major fragments of the aircraft and destroyed structural components of the towers, including their mass, approximate size, speed, and trajectory will be developed in the global analysis of aircraft impact into WTC 1 and WTC 2. The trajectory of each fragment will consist of the initial point of entry, point of exit or resting place. This debris field database will be used to estimate which areas within the impacted floors would likely have lost their fireproofing due to direct impact by debris.

Deformations and Accelerations—Estimates of accelerations and deformations, including localized effects, as a function of time on steel members in each of the two towers will be developed in the global analysis of the aircraft impact. Accelerations will be determined at representative locations on the floor truss systems and columns in the impact-affected zones of both towers (floors 93 to 98 of WTC 1 and floors 78 to 83 of WTC 2). These accelerations will be compared with the threshold values estimated from the adhesion and cohesion properties of SFRM developed in the experimental and analytical study presented below to estimate the likely extent of damage to the fireproofing on the columns and floor systems.

Preliminary results from the subassembly impact analysis of an aircraft engine into a strip of the towers with a width and height of single exterior panel (three exterior columns width and three floor height) extending all the way through the core indicate that the accelerations on the lower chords of floor trusses will need further analysis to account for high frequency vibrations and the short-duration sharp peaks in the computed acceleration time-histories and their effects on damage to SFRM. One possible approach is to low-pass filter the acceleration records to remove these high-frequency vibrations. Another approach is to develop "shock spectra" for a number of steel members with fireproofing configurations using finite element analysis to determine, for a given frequency, the acceleration amplitude that is needed to dislodge the fireproofing based on its adhesive and cohesive strength. The shock spectra will then be compared with spectra of the calculated acceleration time-histories to estimate the extent of damage to the fireproofing.

I.5.1 Mechanical Properties of SFRM

The purpose of these tests is to develop a rational basis for estimating the extent of loss of SFRM as a result of impact loads on protected members. Tests will (1) determine the mechanical properties of CAFCO BLAZE-SHIELD Type DC/F, and (2) verify models for estimating loss of fireproofing when a protected member is subjected to impact-induced vibration. The mechanical properties to be measured are:

- SFRM cohesive strength, and
- SFRM adhesive strength to steel substrates with and without primer.

The adhesive and cohesive strengths will be measured for static loads, as described below for Phase I tests. The tests will be done on 1/4 in. thick steel plate specimens, with and without primer (Tnemec Series 10 red primer), and for nominal SFRM thickness of 3/4 in. and 1 1/2 in. Specimens are fabricated and testing will be done during June and July, 2004.

From the measured strength properties, estimates will be made of the local accelerations required to damage or dislodge the SFRM, as described below. These estimates will be verified by impact tests of plates and bars covered with SFRM and instrumented with accelerometers, as described in the Phase II tests.

Phase I—Tensile Pull-off Test to Measure Adhesive Bond Strength and Cohesive Strength

Specimen—Steel plates (8 by 16 by 1/4 in.) with CAFCO BLAZE-SHIELD Type DC/F and nominal thickness of 3/4 in. and 1 1/2 in.

Pull-Off Test Procedure (see Fig. I–16)

- Using a fine-tooth saw, cut into SFRM applied to plate to obtain 2 3/4 in. square test specimens to ensure that the area resisting the applied load is well defined.
- Affix aluminum plates with two-component adhesive.
- Allow adhesive to cure.
- Measure force required to pull off the plate.
- Record load and note failure mode (cohesive, adhesive, mixed).

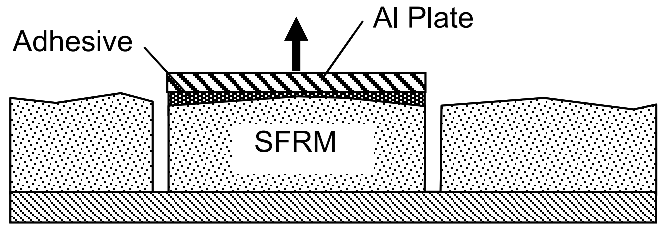


Figure I–16. Pull-off test of SFRM applied to steel plate.

If all failures are adhesive, the cohesive strength will be determined by bonding the SFRM block to a steel plate with adhesive and repeating the test.

Phase II—Verification of Models to Predict Dislodgement of SFRM

Impact tests of plate and bar specimens will be done to determine the impact loads needed to produce different levels of accelerations. Plates and bars with SFRM will be subjected to different levels of impact until the SFRM is dislodged. Two simplified models will be used to estimate the relationships between material strengths and impact required to dislodge the SFRM. Model predictions will be compared with test results.

CASE 1: Planar Element

The simplified model considers the substrate and SFRM as rigid bodies. The SFRM would dislodge when the inertial force exceeds the smaller of the adhesive bond strength or cohesive strength. Figure I–17, shows the free body of the fireproofing being acted upon by its inertial force and the adhesive force. The acceleration to dislodge the SFRM is:

$$a = \frac{f_b}{\rho \, t} \tag{I.1}$$

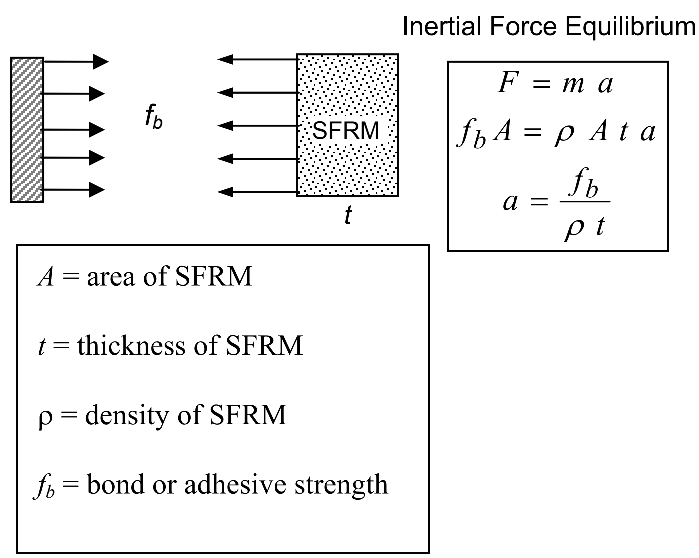


Figure I–17. Derivation of acceleration to dislodge SFRM from planar substrate.

where:

f_b = bond or adhesive strength

t = thickness of SFRM

ρ = density of SFRM

For example, for an SFRM with cohesive and adhesive strength of 150 psf, a density of 15 pcf, and an applied thickness t = 1 in., we would find that a = 119g, where g is the gravitational acceleration. This shows that acceleration on the order of 100g would be required to dislodge this SFRM from a planar surface.

CASE 2: Encased Round Element

Again, a rigid body model is used. In this case, the SFRM would mobilize its cohesive tensile strength, f_t, and adhesive bond strength, f_b. Figure I–18 shows the derivation for the relationship between material strengths and acceleration to dislodge the SFRM from a round bar. The required acceleration is as follows:

$$a = \frac{4 f_t (d_0 + (\alpha - 1) d_i)}{(d_0^2 - d_i^2) \rho \pi} \tag{I.2}$$

where:

f_t = cohesive tensile strength of SFRM

d_0 = outside diameter of SFRM

Inertial Force Equilibrium

$$\text{Mass} = m = \pi \frac{(d_o^2 - d_i^2)}{4} \rho$$

$$F = f_t (d_o - d_i) + f_b d_i$$

$$\text{Let} \quad f_b = \alpha \, f_t$$

$$F = f_t (d_o + (\alpha - 1) d_i) = \pi \frac{(d_o^2 - d_i^2)}{4} \rho \, a$$

$$a = \frac{4 f_t (d_o + (\alpha - 1) d_i)}{(d_o^2 - d_i^2) \rho \pi}$$

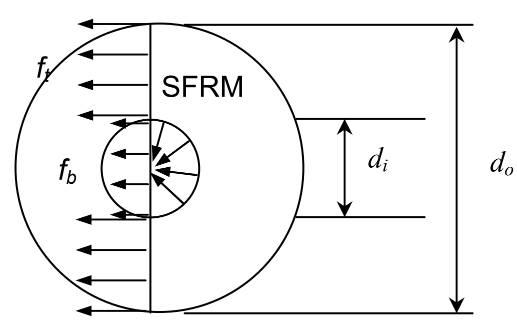


Figure I–18. Derivation of acceleration to dislodge SFRM surrounding a round bar.

d_i = steel bar diameter

α = Rrtio of bond strength to cohesive strength of SFRM

ρ = Ddnsity of SFRM

For example, if the steel bar has a diameter of d_i = 1 in., the SFRM has an outside diameter of d_0 = 2 in., a density ρ = 15 pcf, a cohesive tensile strength of f_t = 300 psf, and a bond strength to cohesive strength ratio of α = 0.5, we would find that an acceleration of a = 152g is required to dislodge the SFRM from the bar.

I.6 SUMMARY

This appendix has focused on conditions of the fireproofing (or SFRM) in the WTC towers before and after aircraft impact. Results of simplified finite-element simulations of heat transfer under fire conditions have shown that variability in thickness of fireproofing reduces the effectiveness of the fireproofing so that protection is less than implied by the average thickness of the fireproofing. As a result, the NIST-led investigation sought available information on the in-place condition of the SFRM used in the WTC towers. Limited information was provided by the Port Authority in the form of thickness measurements taken at various times during the 1990s. Additional information was obtained from photographs of floor trusses provided to NIST. Analysis of the data indicated that fireproofing thickness was variable, as would be expected for application to floor truss members with small cross sections. Based on analyses of the available data, the following values were taken to be representative of the SFRM thickness on the floor trusses:

- Original SFRM: Average thickness of 0.75 in. with a standard deviation of 0.3 in. (coefficient of variation = 0.40)
- Upgraded SFRM: Average thickness of 2.5 in. with a standard deviation of 0.6 in. (coefficient of variation = 0.24)

Based on finite-element simulations of a 1 in. round bar covered with SFRM having lognormal distributions for thickness that are consistent with the above values, it is concluded that the original fireproofing on the floor trusses is equivalent to a uniform thickness of 0.6 in. and the upgraded fireproofing is equivalent to a uniform thickness of 2.2 in.

No information is available on in-place conditions of the fireproofing on the exterior columns and spandrel beams, and little information is available on the conditions of fireproofing on core beams and columns. In subsequent thermal analyses, the fireproofing on these elements will be taken to have uniform thicknesses equal to the specified values. This assumption is believed to be justified by the offsetting factors of measured average thicknesses tending to be greater than specified thicknesses and the reduced effectiveness of a given average thickness of fireproofing due to thickness variability.

Another objective of this appendix is to review the methodology that will be used to estimate how much of the SFRM may have dislodged as result of aircraft impact. Simple static models have been developed for an order of magnitude estimate of the acceleration that would be required to dislodge the SFRM. Based on these models and assumed, but representative, values of density and strength (adhesive and cohesive), it is estimated that acceleration on the order of 100g to 150g (where g is the acceleration due to gravity) would be needed dislodge the fireproofing. Additional analytical studies will be conducted to account for dynamic effects, and tests will be performed to verify these predictions.