Exposed Steel Framing on High Rise Buildings

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MODERN ARCHITECTURE is imposing greater and greater demands on integration and expression of structural materials in building design, and steel is very much a part of this trend. Steel, however, must no longer be considered an assembly of beams and columns forming the supporting framework or "skeleton" of the building, encased in fire protective material. The skeleton is coming out of the closet. Architectural use of exposed steel is growing steadily as more and more design possibilities are explored and adopted. Many buildings in cities throughout this country and Europe have already been designed and constructed using exposed steel framing to varying degrees.

It has long been considered by architects and engineers, however, that fire protection is one of the main problems in using exposed steel, particularly in high rise buildings. Much research by AISI, AISC, UL, and ASTM has been accomplished and is still underway, updating fire protection technology to enable proper and safe design by architects and engineers.

UNITED STATES STEEL BUILDING, NEW YORK CITY

As part of an overall applied research program, prior to the design of a new 54-story rental office building in New York City sponsored by United States Steel Corp., an important segment of the research program was devoted to different fire protection methods, with emphasis on exposed steel. New protective coverings, protection by shielding, water cooling, and elevated temperature steel designs were all studied for various building prototypes expressing exposed steel to varying degrees.

The prototype totally expressing structure, with exposed steel plate girder spandrels spanning 54 ft and extending full depth between windows, was adopted for the final design (Figs. 1 and 2). The spandrel members consist of 70-in. deep steel built-up girders with metal cladding and window frames attached to top and bottom flanges forming the entire exterior wall assembly. As a structural member, the girder supports cladding, window frames and a portion of the interior floor construction; as the exterior wall it provides the weatherproof building enclosure in addition to the windows and exterior columns. The exterior face of the steel web will receive a three-coat paint finish. Top and bottom steel flanges and interior steel surfaces of the girder will all receive a spray on application of mineral fiber or vermiculite type fireproofing. See Fig. 3. The cladding described above, attached to the flanges of the structural steel girder, also forms the fire canopy which, together with the interior web and girder flange fireproofing, prevents steel temperature from reaching critical levels under fire conditions.

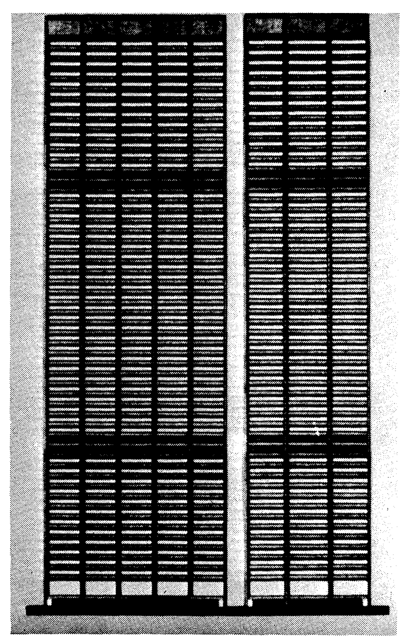

Figure 1

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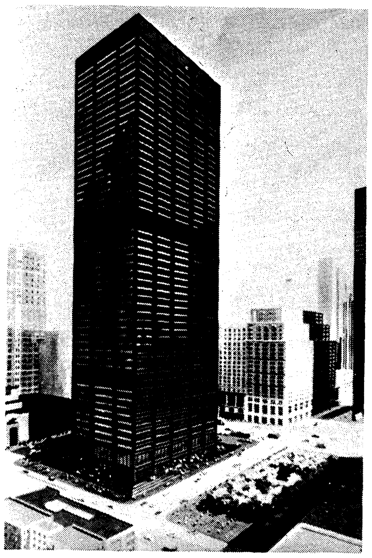

Figure 2

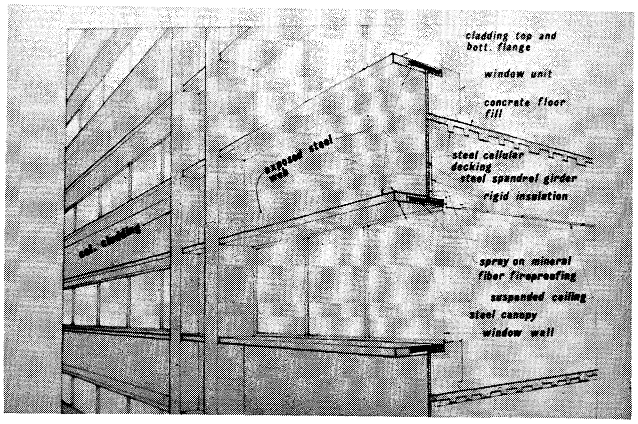

Figure 3

FIRE RATING

The fire resistance rating for this construction element, however, cannot be determined by standard fire tests made in accordance with the *Standard Methods of Fire Tests of Building Construction and Materials* (*ASTM-E119*). A compartment type fire test, such as required in the standard fire test, is neither feasible nor realistic when applied to this exterior construction element. The large window opening size would make it impractical to achieve the required time temperature curve, even if a compartment of suitable size could be constructed for testing purposes. Furthermore, the standard time-temperature curve does not properly represent fire intensity and duration for this type of office occupancy, particularly along the exterior portion of the building. Many tests have demonstrated that higher temperatures occur during the first hour, with far less intensity and duration after the first hour, depending upon the ventilation provided in the exterior wall surfaces.

METHOD OF FIRE PROTECTION PROPOSED

A more realistic approach, based upon a thermodynamic method of analysis for predicting steel surface temperatures and full scale test demonstration confirming that critical steel temperatures of 1000° to 1200° F will not be reached, was recommended and adopted. This approach to fire protection of construction elements in buildings can simply be called a shielding approach, which is commonly used and accepted. Shielding can be accomplished by a barrier (flame impingement shield) or by geometry (distance) or in a combination which, in effect, prevents elevation of steel temperature to critical levels during a real fire without need for total encasement of individual elements. Fire protective ceilings between steel floor members and the source of thermal radiation is one example of barrier shielding commonly permitted in lieu of total encasement of steel members. Roof construction (trusses) more than 20 ft above the floor below without any protective ceiling or encasement of steel framing is already permitted in many building codes for most building classifications and occupancies.

To arrive at a spandrel girder assembly incorporating flame impingement shields and distance as a means of fire protection, a thermodynamic analysis was made. The combination of flame impingement shields, position of the girder, location of window line, size of window opening and interior protection resulting from this analysis will prevent steel temperatures from elevating above 1000° F during a real fire inside the building.

Heat Transfer Analysis—When an unprotected exterior steel building member is exposed to a flame, it will receive heat from the flame and may dissipate heat to its surroundings at lower temperature by processes of radiation and convection. The processes involved are shown schematically in Fig. 4 and are defined by Eqs. (1) and (2). The convection transfer may be either positive or negative, depending upon the value of

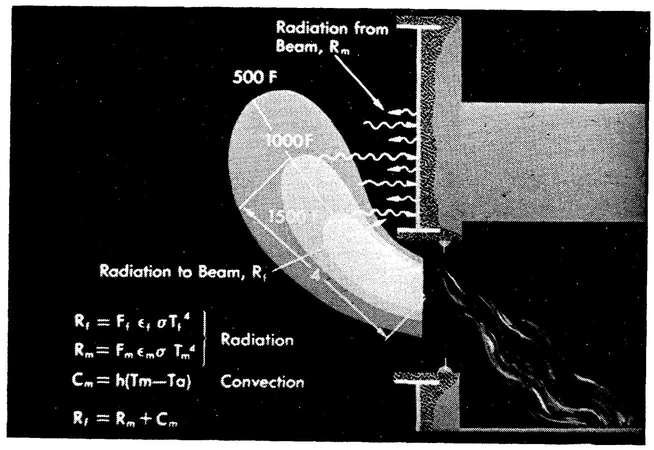

Figure 4

T_a relative to T_m, but in any case a long exposure (longer than about 20 minutes) will result in equilibrium as expressed by Eq. (3). This equation can be solved when the characteristics of the flame and the geometry of the exposure are known. However, the random nature of building fires makes the determination of these factors difficult, and therefore, a general solution has been developed for a range of flame characteristics and geometry. This solution, given in Fig. 5, permits determination of the maximum temperature that will be attained by any exterior surface exposed to fire with or without flame impingement.

To use the figure for a specific case, it is necessary to know the flame temperature, the flame emissivity, and the configuration factors for radiation. For most flames, a value of 0.3 may be used for emissivity. However, lower values may occur in clean-burning fires with a large amount of ventilation. The configuration factor depends on the geometry of the exposure, and varies from 1.0 for cases of direct flame impingement to

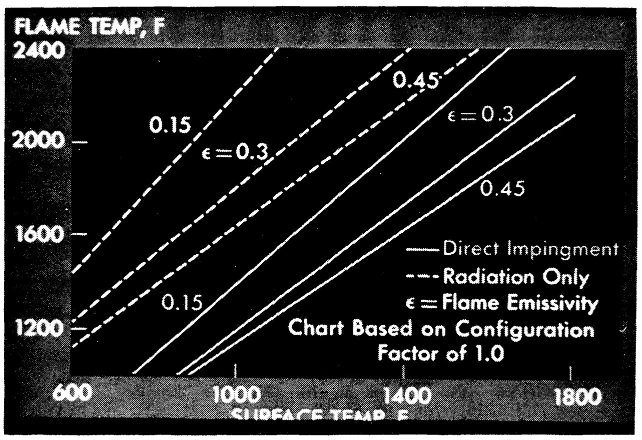

Figure 5

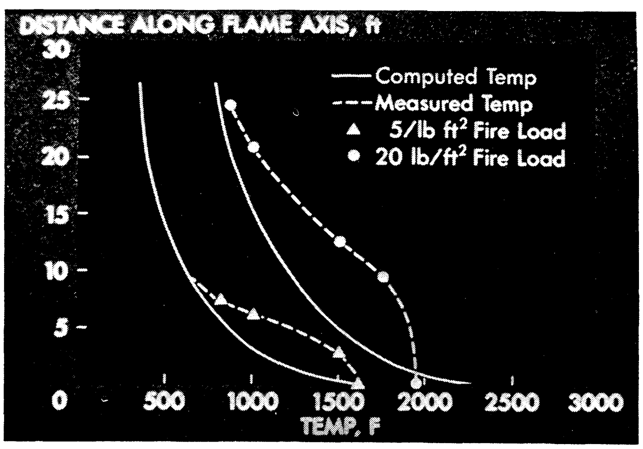

Figure 6

0.0 where members are completely shielded from radiation. A sketch of the anticipated flame pattern in relation to the exposed member will be helpful in evaluating the configuration factor for a specific application. Reference to publications on radiation heat transfer will also be helpful. Figure 5 has been drawn for a configuration factor of 1.0. The flame temperature required for Fig. 5 depends on the design of the building and on the amount and type of combustible material available to burn. A suitable estimate may be made by use of Fig. 6. For a fire load of 5 lbs per sq ft, Fig. 6 indicates a fire temperature of approximately 1600° F at the window and about 1300° F at a distance of 4 feet from the window on the flame center line. Now, if this value of 1300° F is used as the average radiating temperature of the flame as seen by an exterior structural member, the maximum temperature that will be attained by that member may be determined by Fig. 5. If the member is shielded from flame impingement (as in the case of the proposed building), the lines for "radiation only" will apply; and for a flame temperature of 1300° F and emissivity of 0.3, a surface temperature of 680° F is indicated.

Trenton Test—This approach involving the use of flame impingement shields applied to the flanges of the spandrel girders for the proposed buildings was also tested to further demonstrate the validity of the thermodynamic analysis. The test was conducted by Underwriters' Laboratories, Inc., on October 10, 1968, on the grounds of the American Bridge Div. plant in Trenton, N. J., where a full scale mock-up of the proposed building was available.

Description of Building—For the purpose of the fire test, a concrete block enclosure approximately 56 ft wide, 24 ft deep and 9 ft high was added to the mock-up to simulate a typical office building area. See Fig. 7. The roof of the enclosure was constructed of Flexicore slabs, and

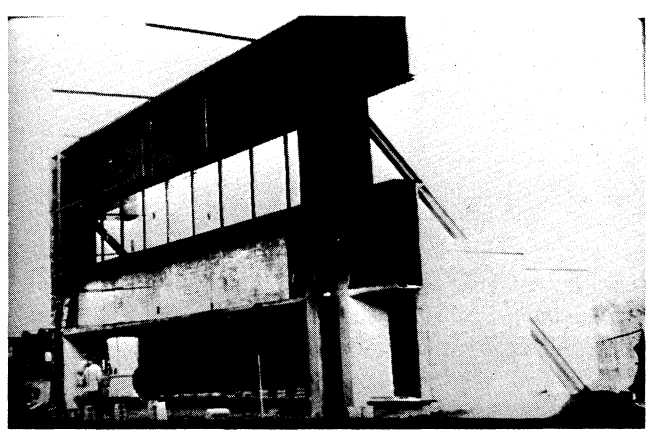

Figure 7

all interior surfaces of the enclosure were sprayed with mineral-fiber fireproofing. The exterior face of the mock-up was painted steel. No fireproof coating was applied to this face except for two small areas of the spandrel girder. One of these areas was coated with a $\frac{3}{16}$-in. layer of "Albi Clad 89" intumescent paint, and the other was protected by a $\frac{9}{16}$-in. coating of "Vonco" fireproofing. These coatings were applied merely to obtain some indication of the effectiveness of these fireproofing materials under conditions of exterior fire exposure.

Temperature Measurements and Fire Load—Temperatures were measured at 17 points on the exterior steel surfaces, at 6 locations inside the building, and at 10 positions in the flame outside the building. All thermocouples were connected to high-speed recorders to provide a complete record of temperature during the test. See Figs. 8 and 9.

Fire load for the test was provided by 5600 lbs of kiln-dried, white fir lumber in the form of wood cribs, each weighing approximately 30 lbs. The cribs were set on 8-in. concrete blocks and distributed uniformly over the floor of the building (Fig. 10).

To assure ignition of the wood, 125 lbs of wood excelsior and 142 lbs of paper excelsior were spread around the cribs and sprinkled with 5 gal of fuel oil. The total combustible content of the building, including the fuel oil and excelsior, represented an equivalent heat content of approximately 5900 lbs of wood. The floor area of this building was 1060 sq ft and, therefore, the total fire load was 5.6 lbs of wood per sq ft.

Description of the Fire—Following ignition of the oil-soaked excelsior, the fire developed quickly and reached temperatures considerably higher than those that would be encountered in the Standard ASTM E-119 Fire Test. Large flames emerged from the window of the fire chamber, and these were held close to the face of the building due to the action of the wind which was blowing at 4 to 8 miles per hour toward the building. See Fig. 11.

About 15 minutes after ignition, the fire was near its maximum intensity. The flames extended nearly to the

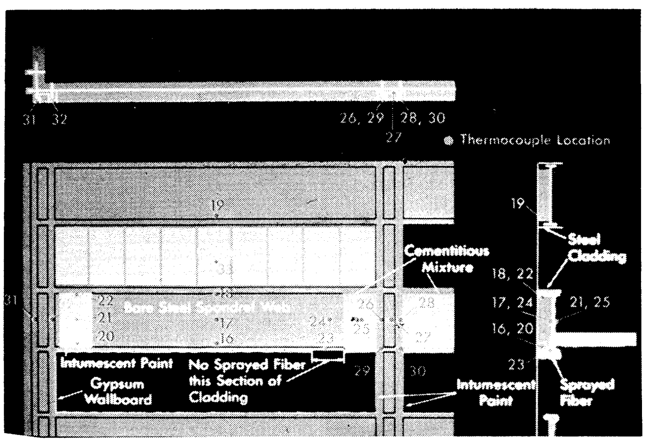

Figure 8

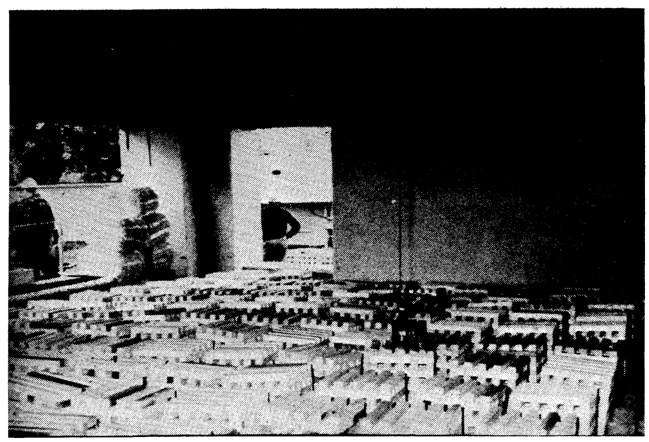

Figure 10

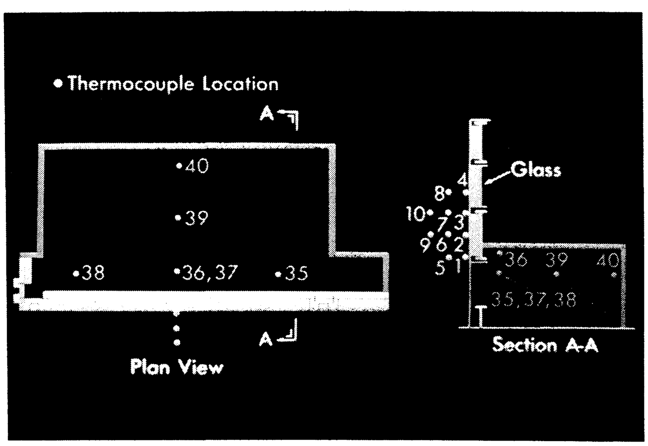

Figure 9

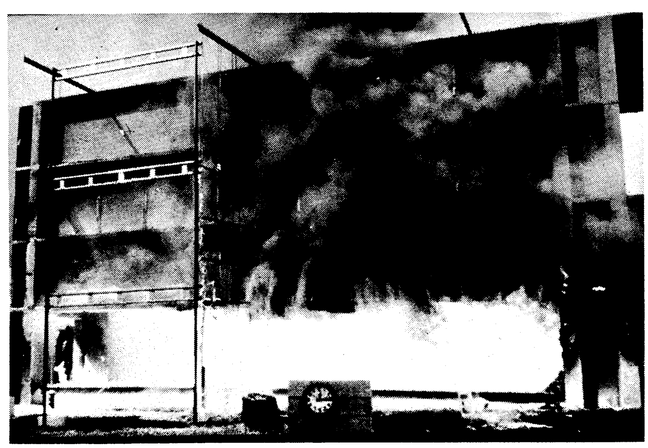

Figure 11

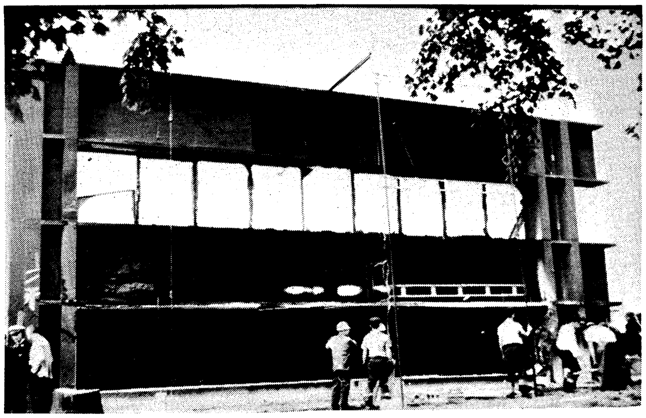

Figure 12

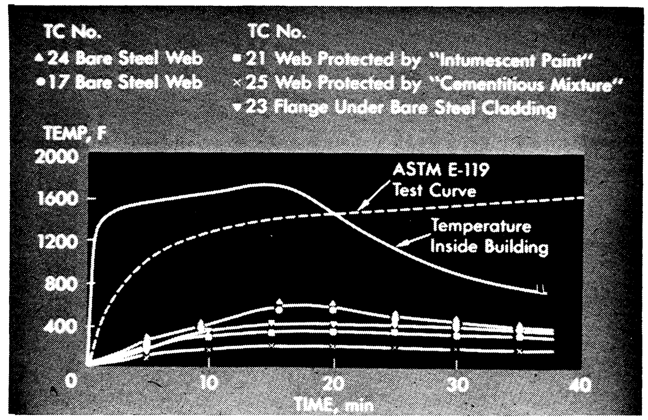

Figure 13

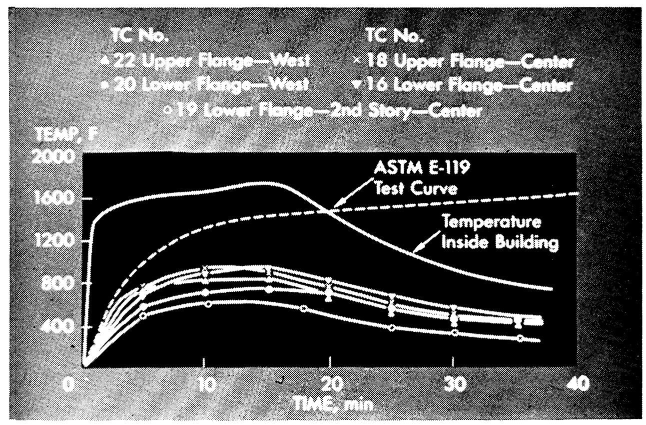

Figure 14

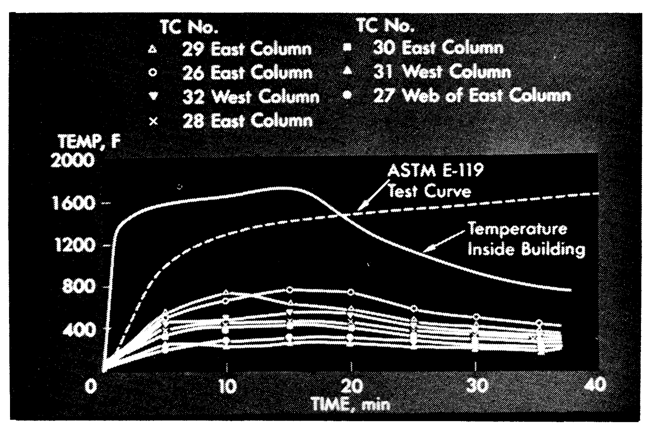

Figure 15

top flange of the spandrel girder, but they did not appear to be in contact with the web of the spandrel in spite of the force of the wind which was blowing toward the building. The average fire temperature inside the building reached 1700° F at 15 minutes after ignition, and at this time, the flame temperature just outside the building near the bottom flange of the spandrel girder was 1500° F. At a point 24 in. away from the center of the spandrel web, the flame temperature had decreased to 1060° F, and near the top flange of the spandrel the temperature was only 920° F. These temperatures are representative of conditions at the time of maximum fire intensity.

A considerable amount of smoke was generated during the first 15 minutes of the fire, and this was carried over the top of the building by the wind. The glass in all the second story windows cracked before 15 minutes of exposure, and the center pane fell out about 30 minutes after ignition. A maximum temperature of 310° F 17 minutes after the start of the fire was indicated by a thermocouple attached to the glass, and cloth strips hanging near the windows to simulate curtains did not ignite.

Test Results—The structure withstood the fire exposure without any damage whatsoever. See Fig. 12. Some of the non-structural elements were affected by the heat. The most evident damage of this nature was the distortion and separation of the bottom flange cladding at the location where the sprayed fiber insulation had been removed before the test. The bottom cladding is for architectural appearance only and is not essential for fire shielding. The shielding is provided by the cladding on top of the spandrel flange which remained substantially intact after the fire. The thermocouple attached to the bottom flange of the spandrel girder at this point of maximum exposure registered a maximum temperature of 420° F. In the proposed building, this spandrel girder flange would be independently fireproofed before the cladding is applied.

Spandrel Girder Temperatures—The maximum temperature reached by the bare web of this beam was 640° F at 16 minutes after the start of the fire. This is well below the safe temperature limit of 1000° to 1200° F for structural steel. Therefore, it is evident that the web of the spandrel girder was adequately protected from flame impinge-

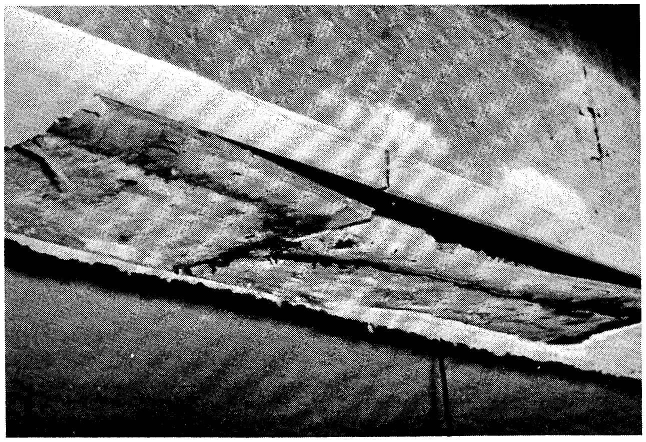

Figure 16

ment by the steel cladding surrounding the spandrel girder flange. The effectiveness of this cladding as a flame shield during this test is especially significant because the wind was blowing the flame toward the face of the building.

The maximum temperatures reached by the insulated portions of the spandrel girder web were 390° F for "Albi Clad 89" protection and 220° F for "Vonco." It is clear that both of these materials have significant fire resistance properties. However, in view of the effectiveness of the flame shielding principle, it is obviously not necessary to apply fireproofing material to the exterior face of the spandrel girder web. Figures 13, 14, and 15 show plots of sample test results for web, flange, and column, respectively.

Conditions of Spandrel Girder—At the end of the test, it was found that no permanent deflection, buckling or structural damage to the spandrel girder had occurred which would affect its structural adequacy.

Condition of Steel Cladding—Visible damage to the steel cladding was observed in the vicinity of thermocouple 23. (No sprayed fiber was provided in this area.) This damage was confined to the underside only. The flame impingement shield remained intact and performed throughout the test to prevent direct flame impingement on the steel web of the spandrel girder. See Fig. 16.

CONCLUSIONS

On the basis of the thermodynamic analysis and test described above, the following conclusions may be reached:

1. The use of flame impingement shields as described herein is the most efficient and effective method of protecting exterior steel spandrel girders from the effects of fire inside the building.
2. For the particular building simulated in the fire test reported here, the shielded exterior spandrel girder web reached a maximum temperature of 640° F during a severe fire resulting from the rapid burning of a typical office fire load. This temperature is well below the limiting range of 1000° to 1200° F for structural steel. This proves conclusively that the wall assembly and method of fire protection of the U. S. Steel Building meets required performance standards.