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# The Analysis, Design and Remedial Repairs for a Fire Damaged Two-Way Roof Truss Structure

Calcul, projet et réparations d'une charpente métallique endommagée par le feu

Berechnung, Entwurf und Überholungsarbeiten an einer brandgeschädigten Dachkonstruktion

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## 1. Introduction

The structural problems presented by fire damage to a structure are numerous in that many effects not normally considered in the design of structures must be taken into account. These problems are especially acute with steel structures where the tensile strength and yield strength of the material decreases drastically at temperatures above 370°C. This temperature is easily reached in a building fire of short duration.

Several publications (1,2) and textbooks are available to assist the structural engineer in the consideration of thermal effects on various grades of steel at high temperatures. However, these references are primarily concerned with the ability of steel to withstand continuous sustained high temperatures and not to assess the performance of steel under continuous high temperatures for relatively short periods of time.

A major consideration which the structural engineer must take into account is when steel is subjected to high temperature, it expands, reducing the modulus of elasticity of the steel. As a result of expansion, additional forces are applied to adjacent restraint points located in cooler parts of the structure. This additional force can result in increases in stress or stress reversals in adjacent areas of the building.

To determine the full effect of a fire on structural steel, one must have a fairly good idea of what happens to the steel during such an exposure. Complicating the problem of determining the effects are numerous uncertainties such as:

a. Temperature attained by the steel is hard to determine and can only be estimated.

b. Time of exposure at a given temperature is unknown.

c. Heating is uneven.

d. Cooling rates vary and are often subjected to sudden quenching through contact with water as the fire is extinguished.

e. Steel is usually under load and restrained from normal expansion.

f. Microstructural changes in material properties are often uneven throughout a particular member.

## 2. Structural System

It is the intent herein to describe one approach to the analysis, design, and remedial repairs to a 106 meter by 106 meter roof structure due to a sudden, intense fire of short duration in the roof area. The structure is the physical education, athletic and convocation center at Middle Tennessee State University in Murfreesboro, Tennessee. The architects for the project are Taylor & Crabtree of Nashville, and the structural engineers for the roof structure are Stanley D. Lindsey and Associates, Ltd., of

Nashville. The roof framework is a symmetrical two-way truss system supported on four columns as shown in Figure 1. The structural system is considered a space grid to obtain the local distribution on each truss. The four main support trusses spanning between the four columns serve to distribute the load equally to the support columns.

The roof structure was analyzed as a two-way grid system under transverse loading, with the member moments and shears being applied to the joints of the corresponding trusses. Due to the symmetry of the roof framework, only one-eighth of the total grid was analyzed using standard matrix methods of analysis. Numerous grid loading situations were considered to determine the maximum stress within each individual truss member. The resulting truss elevations are shown in Figure 2. Volunteer Structures, Inc. of Nashville fabricated the steel to form individual sections, some 8.84 meters and others 15.24 meters in length, and all 3.96 meters deep. The individual sections were joined at the site to form one large square. Extensive use of U. S. Steel's EX TEN 50 high strength steel was made throughout the structure. A490 high strength bolts were used for the main truss connections.

## 3. Structural Fire Damage

During the construction stage of the project (after all steel trusses, bar joists, and roof decking were in place and with the majority of the dead load present), a flash fire broke out on a scaffolding platform adjacent to and just below one of the mechanical rooms. This was just to the side and at midspan of one of the main support trusses. While the fire was under control within thirty minutes, the heat in the roof reached a minimum temperature of 540°C causing a major reduction in the strength of the steel and expansion of several of the truss members. As a result of these changes, several members deformed, thus weakening the structure and causing it to be on the verge of collapse. Immediate action was necessary.

Upon receiving proper authorization to save the structure, temporary shoring and bracing were placed in the area of greatest damage. Before installation of the shoring tower could be completed, the roof structure gave a loud "crack," and the main truss dropped 5 to 7.5 centimeters, as later verified by measurement. The structure remained standing; however, a considerable increase in deflections was apparent. As soon as the main shoring towers were in place under the main support truss, the truss was jacked back up 2.54-3.8 centimeters in an effort to eliminate the large deflections and to relieve stresses in the truss. The problem then became one of trying to assess the extent of the structural damage by deciding which members were no longer effective; the extent of the stress redistribution; and, ultimately the structural soundness of the roof once the full live load was placed on the structure.

An inspection of the damaged area revealed the following physical changes:

a. The top chord of the main support truss had major flange buckling and lateral deformations.

b. Virtually all bar joists and bridging were damaged beyond repair.

c. The top chords of several adjacent trusses had warped stems.

d. Several diagonals composed of double angles had buckled.

e. Virtually all the miscellaneous support steel for the mechanical equipment was deformed.

The above changes plus the large deflected positions of the trusses in the area resulted in a structural system substantially different from the original design.

Based on microstructural studies of A36 steel from the area of the fire excessive grain growth did not occur. Hardness measurements on damaged material indicated that the mechanical properties were still in the acceptable range, and the A490 bolts appeared to be undamaged and should not have to be replaced. The exact temperature reached was not known; however, cooling curves of material which had been partially melted indicated the temperature reached at least 540°C and the maximum temperature was probably below 650°C or of very short duration. The problem was one of trying to analyze and correct the structure as best one could due to large deformations present.

## 4. Structural Repairs

An extensive analytical investigation into the structural problems presented by the damage to the roof structure from the fire was undertaken. A structural model was formulated which predicted reasonably well the behavior of the structure as defined by inspection and displacement measurements. This model was based on the original design model with the panel that buckled (top chord of truss 3A) being zero effective. By modeling the structure this way, while not an exact solution, the analysis yielded a set of design parameters which were an upper bound for existing and future member loads and thus assured that all areas of stress redistribution were adequately anticipated.

Once the structure model was developed, modifications to this model were made to determine action necessary to correct the damaged zone. While many different modifications were considered, only three approaches seemed feasible. These approaches were:

a. The possibility of reshoring and jacking the entire structure back to its original elevation and replacing those members, joists, bridging, etc. which were damaged by the fire.

b. The possibility of reshoring and jacking a portion of the structure around the damaged zone to its original elevation. Once this was done, these members, joists, etc., which were damaged by the fire could be replaced.

c. The possibility of reinforcing the structure in its current condition (i.e., at some intermediate elevation and braced by cables and shores as mentioned). Those members and connections which received more than their design load with the addition of live load would be reinforced, and the joists. bridging, etc., which were damaged by the fire would be replaced.

Our investigation showed that of the three different approaches, only the first and third approaches were feasible. These approaches, hereafter referred to as Option 1 and 2 respectively, are discussed herein. The second approach was not feasible due to the limiting capacity of commercial shores available to lift only a portion of the truss structure back to its original elevation and the serious stress reversal that would occur in adjacent truss members making reinforcing practically impossible.

The first option was that of reshoring and jacking the truss structure back to its original elevation and replacing those members, joists, etc., that were damaged by the fire. This procedure required the same shoring arrangements that were defined for the construction stage of the project. Once the truss was in its original elevation, the damaged members, joists, and bridging would have to be replaced. The buckled portion of the top chord truss 3A would have to be replaced while the top chord of truss 2 at mid-span of truss 6 and truss 7 would have to be reinforced. Also, it was decided that all high strength bolts in the top chord connections at the intersection of trusses 6 and 7 and truss 3 should be replaced individually once the roof structure is back to its zero elevation.

The apparent advantage of this option was that it returned the structural system to its original design before the fire with the exception of the reinforcement of the top chord of truss 2 and the two splices required to insert a new top chord section of truss 3. The deflections were then very close to the original design deflections. The apparent disadvantages were that the entire structure must be reshored back to its zero elevation and thus restrict work underneath the roof structure. This in turn could result in a delay in the project plan plus increase the labor involved in reshoring and jacking. Also, it should be noted that while the shoring pattern to raise the truss was defined, the jacking procedure was not well defined due to the new unsymmetrical deflection pattern. For this reason, the jacking procedure could result in stress reversals causing some tension members to buckle and as such must be monitored closely.

The second option was one of reinforcing the structure in its current state for live load and replacing the secondary members, joists, bridging, etc., which were damaged in the fire. Also, overstressed connections in both the top and bottom chord planes would need to be reinforced.

Since all members and connections must be reinforced to within the allowable stress for total design load, additional steel must be added to the truss in the overstressed areas. Likewise, the connections must be reinforced to carry the additional increase in force due to both the increase in dead load as well as the stress redistribution of the damaged structure. Once these corrections are made to the damaged structure, the system would be structurally sound. The only noticeable difference, in that the truss superstructure will be covered up, is that of an increase in deflection on the exterior facia under design loads.

The advantage of this option is that it results in a new structural system which is structurally safe without the addition of new shores. As such, work could continue underneath the roof structure. The disadvantages are that a large increase in pounds of steel would result in the damaged area in that 13 top chord members, 10 bottom chord members, 44 diagonal members, and 12 connections must be reinforced. This procedure results in the addition of approximately 25,373 kilograms of reinforcing members (plates, angles, and structural ties) plus the labor involved in this many corrections. Also, a non-symmetrical displacement pattern results.

Our investigation indicated that the two options to the correction of the damage to the truss structure as presented above were feasible and would result in a structural system which was structurally safe.

It was the concensus of all concerned that Option 2 would be the better of the two options. The corrections were made and the facility is now operational. The building has been subjected to approximately its full design load without unrealistic increases in deflections as predicted by the analytical model and based on later long term measurements.

REFERENCES

1. Fire-Resistant Steel-Frame Construction, 2nd Edition, American Iron and Steel Institute.
2. Manual of Steel Construction, 7th Edition, American Institute of Steel Construction.

SUMMARY

This paper describes the analysis, design and remedial work to a two-way steel roof truss damaged by a sudden, intense, flash fire of short duration in the main support area. As a result of the fire several members deformed, thus weakening the strucutre and causing the roof to be on the verge of collapse. The changes in the structural geometry due to permanent deformations, the resulting re-analysis of the roof frame, and the repairs required to return the structure to as close to the original design as possible are presented.

RESUME

Cet article décrit le calcul, le projet et les réparations d'une charpente métallique subitement endommagée par un feu violent et de courte durée dans la principale région d'appui. Le feu a déformé plusieurs membres et affaiblit l'ouvrage, de sorte que le toît s'est trouvé sur le point d'effondrement. L'étude traite les changements de géométrie de la structure dus aux déformations permanentes, l'analyse résultant de la charpente et les réparations à effectuer pour que l'ouvrage corresponde à nouveau, aussi fidèlement que possible, à sa conception d'origine.

ZUSAMMENFASSUNG

Diese Arbeit beschreibt die Berechnung, Entwurf und die nötigen Ueberholungsarbeiten an einer brandgeschädigten, dachtragenden Trägerkonstruktion. Die wichtigsten Tragelemente wurden durch kurzzeitige sehr intensive Feuereinwirkung geschädigt, so dass einige Tragelemente verformt wurden und die Gefahr des Einsturzes bestand. Die aus der Verformung resultierenden strukturellen Aenderungen wurden in die Neuberechnung aufgenommen; die nötigen Ausbesserungsarbeiten, um die Konstruktion der alten soweit als möglich anzugleichen, werden näher beschrieben.

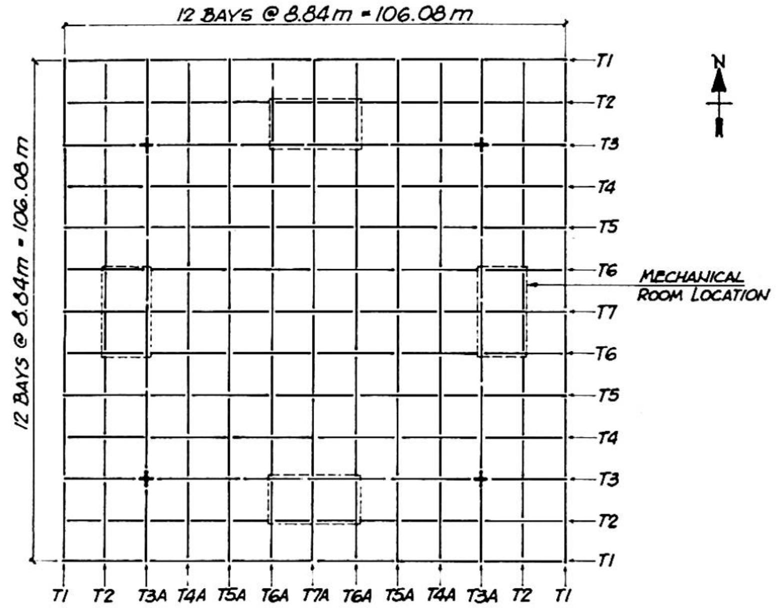
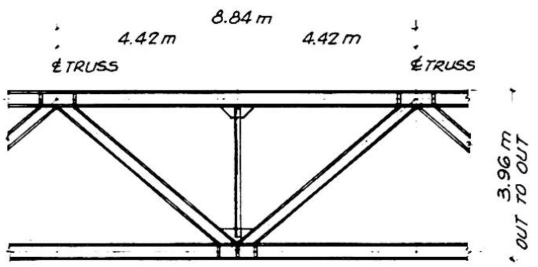
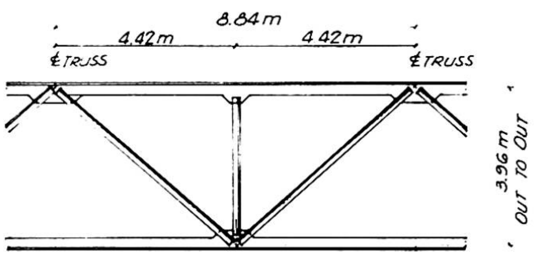



FIGURE 1. ROOF FRAMING PLAN




a) MAIN SUPPORT TRUSS




b) SECONDARY SUPPORT TRUSS

FIGURE 2. TRUSS ELEVATIONS