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AN ASSESSMENT OF THE USE OF STRUCTURAL DEFORMATION AS A METHOD OF DETERMINING AREA OF FIRE ORIGIN

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ABSTRACT

Current methodologies of origin investigation have yet to include the structural deformations seen in steel buildings as a viable indicator of the area of origin of a given fire. As many steel structures are of relatively large size, it is often difficult to determine the area of origin using the typical dig and sift methods advocated in NFPA 921, especially if the extent of the fire was large and there were no witnesses as to the origin of the fire. As has been investigated for years, the performance of steel is highly affected by the application of heat. The science of predicting the deformations of steel members is such that an investigator may be able to “reverse engineer” the fire to get an idea of its relative growth rate and length of combustion even if it is not possible to compute a heat release rate curve. The information derived from careful analysis of the deformations may also yield valuable input for use in computer fire modeling. Using several example cases, this paper explores the methodology that can be applied in order to use the structural deformations as a viable tool to determine the point of origin of large, single story steel framed structures.

INTRODUCTION

NFPA 921 states that the basic methodology of fire investigation should rely on the use of a systematic approach and attention to all relevant details.¹ In order for a fire investigator to pay attention to all relevant details, it is imperative that they be able to recognize, record, and interpret all of the useful details of a scene. Typically, however, the scene is here today and may be gone tomorrow. Thus on scene documentation at the time of initial investigation is a necessity in order to properly determine the origin and cause of a fire. There are many indicators of a fire’s growth and travel left behind at most scenes. These indicators, when interpreted correctly, will almost always lead the investigator to the true origin of a fire. The real question is: Are these traditional “dig and sift” methods practical or advisable in large loss fires?

Imagine a large warehouse fire, say 150 m by 150 m (500’ by 500’). The warehouse is a total loss. After the initial investigation, it is evident that the fire had spread to over half of the warehouse prior to the first engine company’s arrival. After a defensive fire attack was established the fire burned for over five hours and the fire became fuel controlled and basically self-extinguished. Prior to control of the fire, one of the sides of the building partially collapsed inward. There is 1 meter (3-4 feet) of debris on the floor of the warehouse and no witnesses as to the origin of the fire. Where would the investigation begin? Would it be possible or practical to “dig up” the entire half of the warehouse involved at the beginning of the fire? An investigator’s first guess on where to start should be the immediate area around the collapsed portion of the building.

Why should the location of partial collapse be the first guess as to the origin of the fire? The method presented herein explains in detail the underlying principles and how they can be applied to the investigation of fires as described above along with almost any other fire encountered.

FIRE EFFECTS ON STEEL

While the effects of fire on steel have been long researched and documented, a more in-depth understanding of the exact engineering properties will be necessary to understand exactly what happens when a steel structure deforms to the point of collapse. An understanding of plastic theory and the method in which design engineers perform their analysis on buildings is also a necessity in order to understand this concept.

Steel is an elastoplastic material used in all types of construction. Steel can have varying properties which are dependent upon the amount of carbon and alloying agents used in the production process. Structural steel is generally produced to be ductile as opposed to having a high yield capacity. In steel production, ductility must be traded for strength and vice versa. Steel's behavior at room temperature as well as elevated temperatures is discussed in detail in the following sections.

Modulus of Elasticity and Poisson's Ratio

The elastic modulus, E , is the ratio of stress to the strain it produces. It represents the stress required to produce unit strain.² The elastic modulus of steel is typically assumed to be 200 GPa (29,000 ksi) at room temperature and is subject to variation with temperature increases. The typical point of degradation of strength of steel is approximately 150°C.² At this point, the strain increases under the action of a given stress, and the well defined yield point begins to vanish. It then becomes necessary to use the "proof stress" as the yield stress.²

The variation of the modulus of elasticity and the yield stress of steel can be found in Figure 1 below.

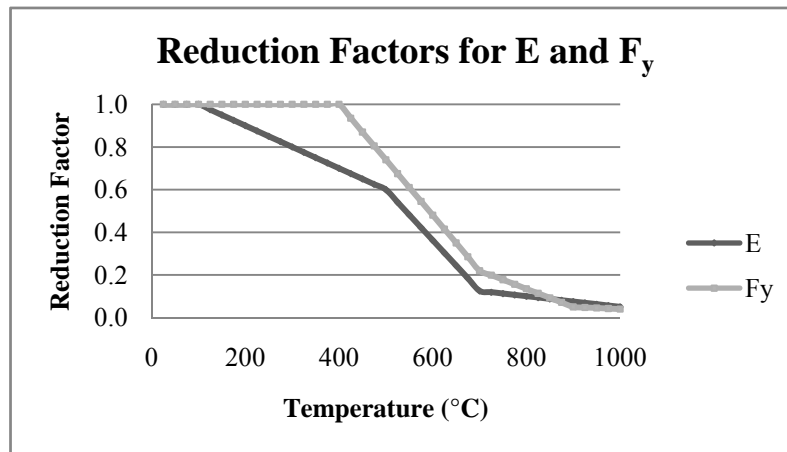


Figure 1: Reduction Factors

Poisson's ratio (ν) is defined as the ratio of lateral strain to longitudinal strain. Poisson's ratio basically quantifies the reduction in cross sectional area as the member is placed into tension or the increase in cross sectional area when the member is placed into compression. According to Cooke, it has been well documented that the Poisson's ratio of steel is negligibly affected by the temperature of the member.² Poisson's ratio for steel will be taken as 0.3 for all calculations in this paper and is the recommended value to use in the field.

Strain in Steel

Deformation of steel members is a function of the strain generated by the three components of strain.³ The three components of strain that are of concern for analysis of deformations induced by fires are thermally induced strain, stress induced strain, and creep induced strain. In a typical structural analysis of a steel member, only stress induced strain is considered since the other two are generally small enough to be neglected. Strain, regardless of type, is defined as the change in length (δ) divided by the original length of the undeformed member (L). The typical maximum strain that structural steel can endure before failure is

20-30% at room temperature.² The deformations incurred at this strain level are generally too high for this to be used as a failure criterion for steel.

Stress related strain is induced by the deformations caused by the loads the member in question is designed to support (i.e. dead loads, live loads, wind loads, etc.). This form of strain is evident in all beams regardless of the thermal loading on the beam. The stress (σ) can be calculated by the accepted methods of structural analysis. Stress related strain can then be calculated as the stress divided by the modulus of elasticity (E) which varies with temperature. As noted earlier room temperature, E is generally taken as 200 GPa (29,000 ksi).

Thermally induced strain is of primary concern during the analysis of steel members during a fire. Almost all materials will expand when heated. The coefficient of thermal expansion dictates how much a certain material will expand when heated. The unrestrained length of a heated member can be found using $L_t = L_0(1 + \alpha T)$, where L_0 is the original length, α is the coefficient of thermal expansion, and T is the change in temperature. The coefficient of thermal expansion is subject to minor variations at increasing temperatures. In an effort to reduce the complication of the calculations, a value of $14 \times 10^{-6}/^\circ\text{C}$ will be used throughout this paper.²

FIRE EFFECTS ON PORTAL FRAMING

According to Buchanan, portal framing systems are typical in large warehouses as well as in commercial establishments and are one of the more prevalent steel building types.³ They are fairly simple to design and even easier to construct. Figure 2 shows an elevation view of a typical portal framed structure. They are widely adaptable since the bay lengths or clear spans can be adjusted with the use of larger structural members to suit the needs of the tenant. Portal frames were chosen for this analysis because of their frequency of use as well as their simplicity to analyze by non-engineering background individuals.

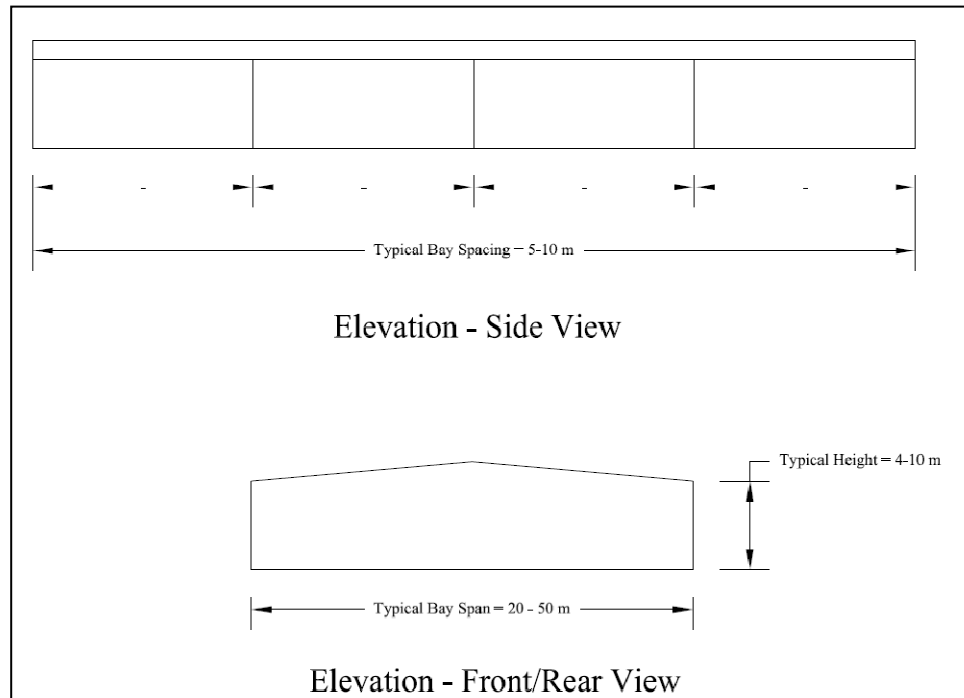


Figure 2: Typical Portal Frame Dimensions

FIRE EFFECTS ON STRUCTURAL COLLAPSE

Due to the weakening of steel members in fire, a building that was well designed to accept the design loads will often undergo significant plastic deformations and possibly total structural failure. Engineers do their design with a factor of safety in mind. A factor of safety is defined as the nominal

resistance divided by the applied force. In structural design, it is possible to see factors of safety as high as 2-3. In other words, the building has a reserve capacity of 2-3 times the anticipated loading. Upon thermal degradation, the nominal resistance is decreased. When the nominal resistance is decreased enough to cause the factor of safety to fall below 1, failure of the structural member will occur.

Another factor that adds to a structure's likelihood of collapse during fire conditions is the addition of unexpected loadings such as firefighting personnel and water from extinguishment efforts. Water can be a large problem for buildings especially if the roof drains have been poorly maintained or the floors have deflected enough to allow the water to pool. All of these factors must be taken into consideration when attempting to use structural deformations to locate the origin of a fire.

Steel design intends to insure that the steel remains in the elastic behavior range under service loads. This is to say that the steel has yet to yield. When fire degrades the structural capacity of a member, the member can quickly enter into the plastic range on the elasticity curve. When this happens, the loading must be redistributed. In the case of a simple beam, this redistribution will not occur since it has no redundancy. Figure 3 below shows the failure mechanism of a simply supported beam along with the general shape of the moment diagram before and after the formation of the plastic hinge at the center.

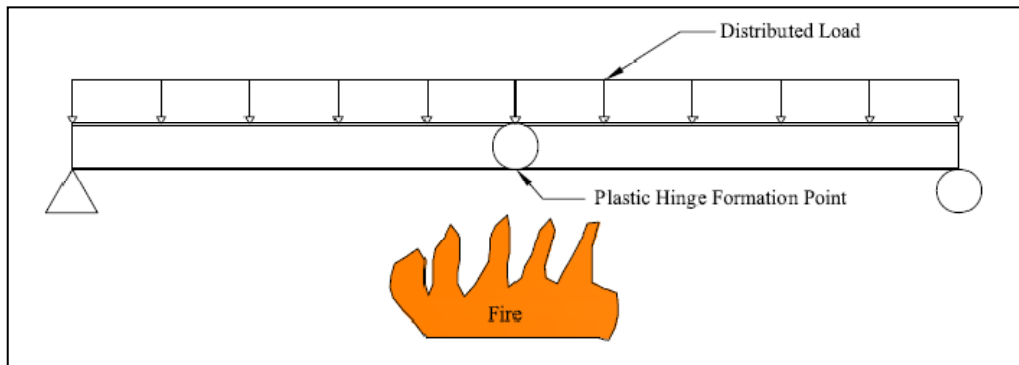


Figure 3: Failure Mechanism of Simply Supported Beam

THEORETICAL EXAMPLES

Simple Beam Example

In the first example analysis, a simply supported steel beam is exposed to a linear time-temperature curve under a uniform load of 43.8 kN/m (3 kips/ft). This example assumes that the steel has no thermal gradients. In other words, the steel receives heat as one mass and is the same temperature throughout.

The steel will yield and suffer plastic deformations when the bending stress is equal to the yield stress. Beams are designed so that the loads placed on them are not sufficient to yield the steel. However, temperature increase is accompanied by a decrease in yield strength. Thus, the beam will fail when the yield stress is reduced to the point where it equals the bending stress.

The deflection of a simply supported beam can be simply found using elastic theory. The AISC Steel Construction Handbook states that the deflection of a simply supported beam with a uniformly distributed load is equal to:⁴

$$\Delta_{max} = \frac{5wl^4}{384EI}$$

Where, w=Distributed Load (N/m)
 l=Length of Beam (m)
 E=Modulus of Elasticity (MPa)
 I=Moment of Inertia (m⁴)

The deflection for a W14x53 section under a uniform load of 43.8 kN/m (3 kips/ft) equates to 17.5 mm (0.69 in). Also, according to the AISC Steel Manual, the unfactored nominal moment capacity is 270 kN-m (199 kip-ft).⁴

This simple equation was set up into a spreadsheet in order to show the general deflection behavior under an increasing thermal loading with no increase in gravity loading. This calculation utilizes the yield stress and modulus of elasticity reduction factors shown in Figure 1. Deflection is mainly a function of the modulus of elasticity. Figure 4 shows the increase in deflection with temperature, and Figure 5 shows the decrease in nominal moment capacity with temperature.

The deflections stop at approximately 600 °C. At that point, this particular beam undergoes plastic deformation and for all practical purposes has failed. In other words, the deflection will increase greatly with no increase in loading since the steel has yielded. Therefore, it can no longer take any additional loading. As can be seen in these figures, the steel has lost its ability to retain the design moment at approximately 400 °C (750 °F). At this particular loading, the beam is expected to fail at approximately 600 °C (1000°F), or when the steel yields. The failure mechanism of a simply supported beam (or bar joist, purlin, or any other simply supported moment resisting member) is demonstrated in Figure 3 on the previous page.

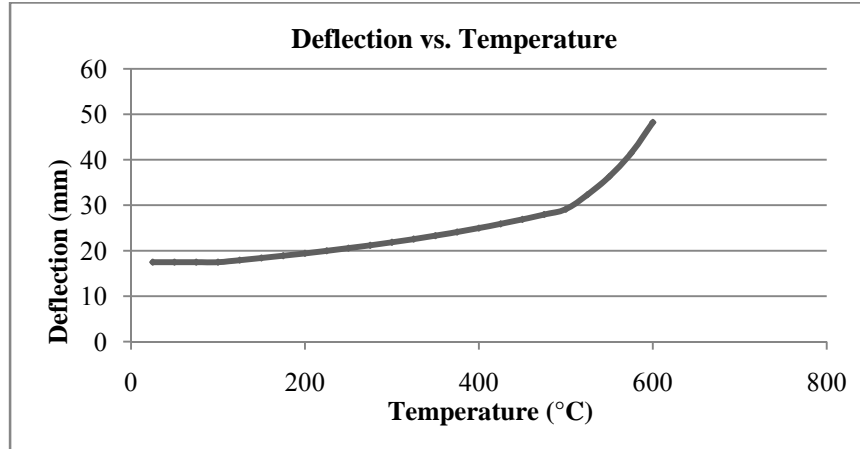


Figure 4: Simply Supported Beam Deflection Behavior under Temperature Loading. Note that the Beam Enters Plastic Deformations at Approximately 600 °C.

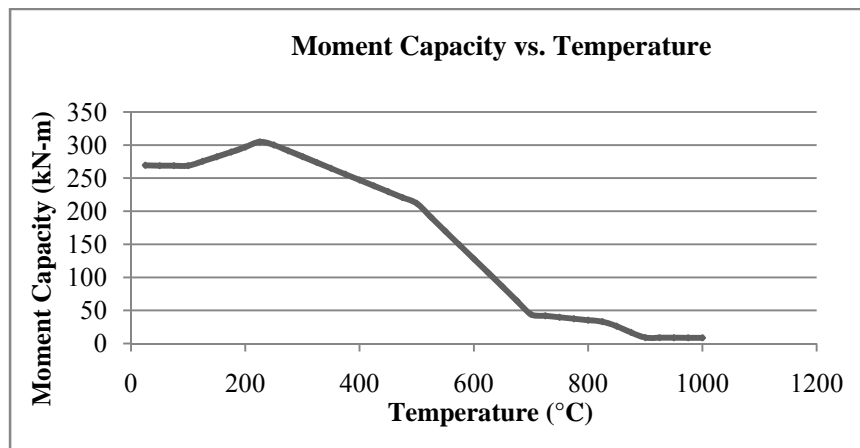


Figure 5: Simply Supported Beam Moment Capacity vs. Temperature.

Finite Element Modeling

A simple finite element model was constructed to show the deformations undergone by a building depending on the origin of the fire. Several modeling conflicts prevented a coupled analysis from being performed. The thermal portion of the model was performed to attain the temperatures of the specific members in the cross section of the portal frame. The degraded modulus of elasticity and yield stress were then imported into a structural model to get the general deflected shape. The member sizes and criteria are not important in this run of models as the purpose is to obtain general deflected shapes. ADINA was used for all finite element modeling. Figures 6 and 7 show the deflected shape with respect to the area of origin of the fire. Also note that the lowest area is not always the area with the most deflection. The most deflection is the point on the frame that has translated from its original position the most.

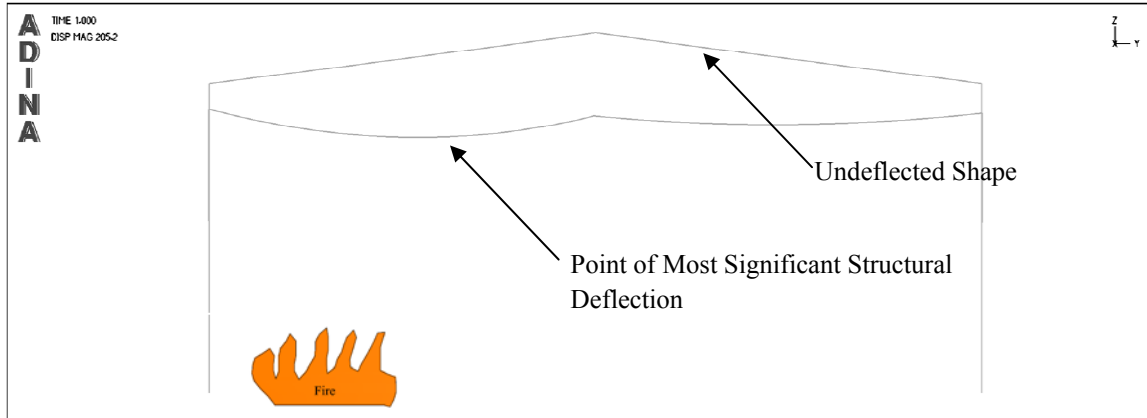


Figure 6: Fire on One Side of Building

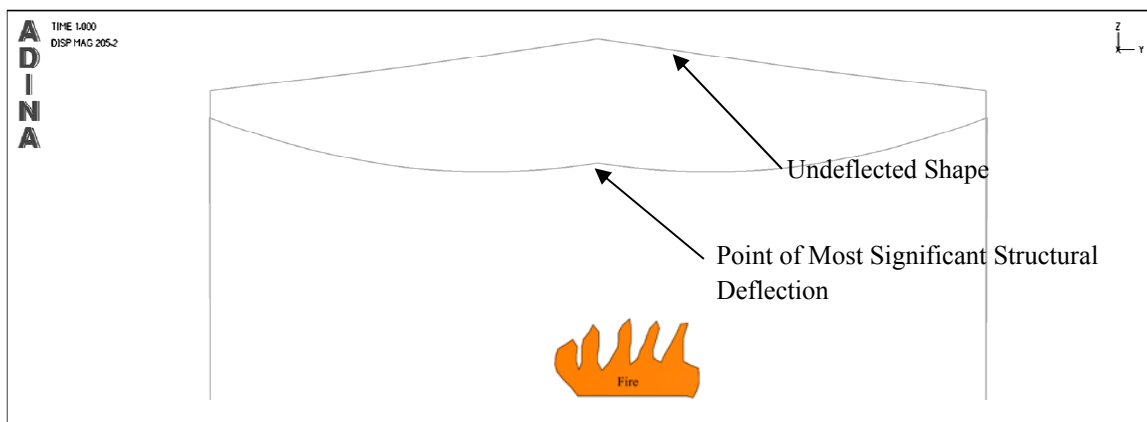


Figure 7: Fire Under Peak of Roof

TRUE EXAMPLES

There are several examples where the use of structural deformations would have significantly shortened the investigation time. While in most cases deformations are noted as a viable indicator, it is rarely used as evidence in an investigative report. The McCormick Place fire in Michigan as well as the Livonia Transmission Plant fire both consisted of a more complicated version of the portal frame design/construction method. Both fires consisted of total destruction of the buildings. Both had witnesses to confirm the area of origin of the fire, so validation of the use of the structural deformations was possible. Figures 8 and 9 show the deformed shapes of McCormick and Livonia, respectively, and their confirmed area of origin.

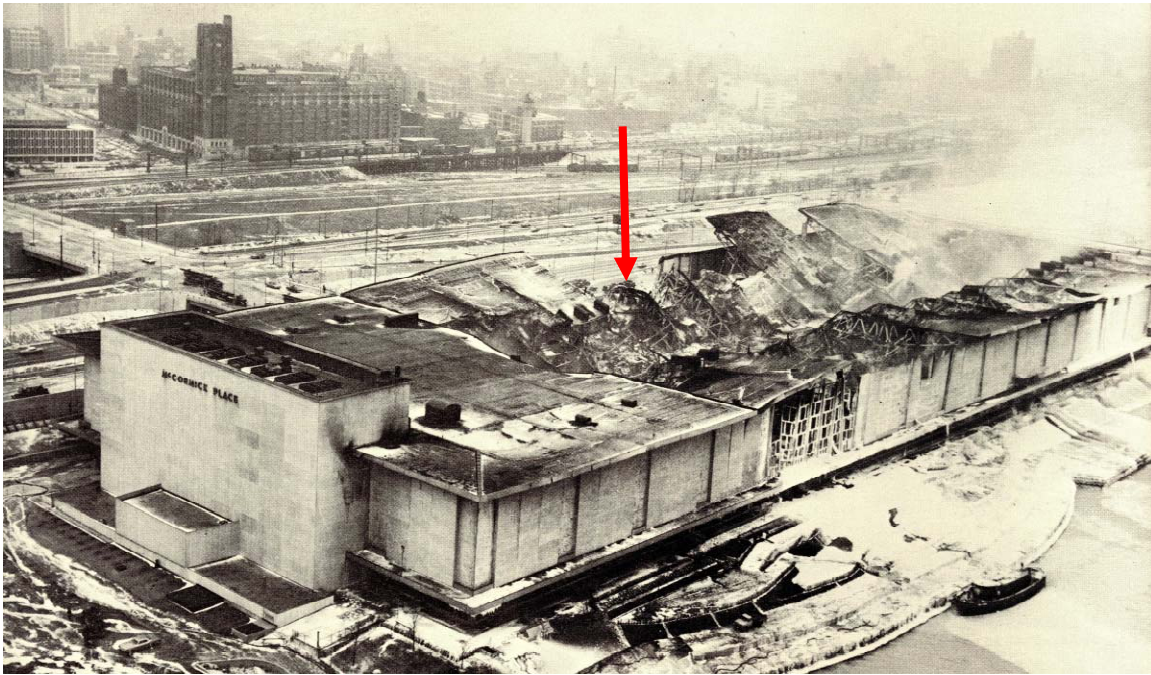


Figure 8: McCormick Place Collapse and Confirmed Area of Origin⁵



Figure 9: Livonia Transmission Plant Partial Collapse and Confirmed Area of Origin⁶

By starting at the areas of partial collapse and high deformation, the investigators would have been able to disregard a lot of the fire debris and had a much easier time finding the area of origin if there had not been

witnesses to point them in the right direction. These two examples are extremely complicated, large loss fires. This method is highly applicable to steel buildings of any size and in almost any condition. Fires involving other materials such as wood can also be solved to a certain extent with this method. The author has noticed in wood structure fires that the area of first roof collapse is almost always above the room of origin. Deflections are not as useful in wood since its properties vary little throughout its noncombustible range of temperatures. Deflections in wood structural members are almost always indiscernible until the complete failure occurs.

DISCUSSION

As a smoke plume reaches the ceiling, it begins to mushroom out over the area of the ceiling (see Figure 10). This smoke plume will generate the most intense temperatures at the point directly over the origin of the fire. As time progresses, the remainder of the room heats up, but the area directly above the origin of the fire will sustain the highest intensity and longest duration of thermal degradation. This fact still holds true even if the room is allowed to reach flashover. It has been proven that the temperatures in a flashover situation will produce a fairly constant temperature throughout the room. The members above the origin of the fire will have the same temperature application throughout the flashover even though the fire directly beneath this point has run out of fuel.

The amount of exposure the steel has to elevated temperatures will determine the amount of strength lost. This would indicate that different members will have differing strengths. The loads will redistribute themselves as much as they can until failure finally occurs. If the fire is stopped prior to a total structural collapse, deflection patterns similar to the above figures should be encountered.

If a fire is allowed to burn long enough, it is possible that most structural members will receive similar heat fluxes and deflect in a similar manner, but this is not a reason to ignore this method. The structural deformations will still be a valid indicator for use in any forensic work to be done after the fire is completed. With the recent advancements in fire and structural modeling, it will be possible to reconstruct a fire and the structure which contained it to “reverse engineer” the scenario. This allows for timeline collaboration with witnesses, added fire load detection, and possibly even arson and/or suppression system sabotage.

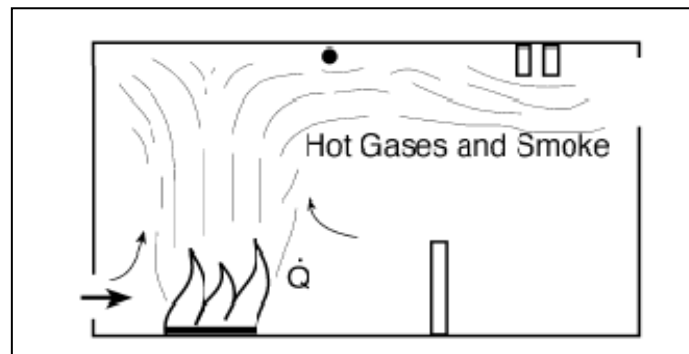


Figure 10: Typical Smoke Filling Pattern of Compartment Fire

CONCLUSIONS

Figures 11 and 12 show a typical fire scenario in a portal frame constructed building. Figure 9 shows a plan view of the scenario. It shows a fire beginning slightly off center and spreading in a radial fashion throughout the structure. While the fires are not located in exactly the same place, Figure 10 shows the probable after fire scenario once it was stopped. The red arrow indicates the probable area of origin. With proper use, this method of investigation can yield much valuable information about the investigation at hand. This information can vary from significantly reducing the amount of time digging in the rubble of a fire to valuable input for an advanced forensic model. The intricacies of this method should be left up to

qualified structural engineers, but the entire scope of this method can be performed by virtually any investigator with a competent amount of knowledge about the behavior of structures.

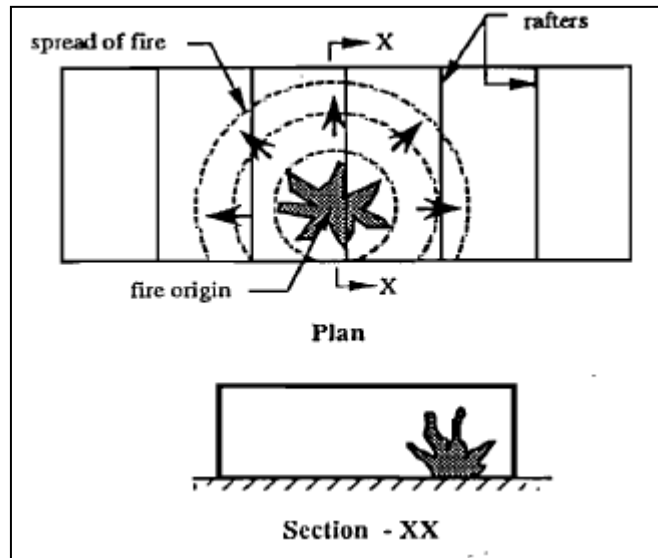


Figure 11: Plan View of Fire within Portal Frame Structure⁷

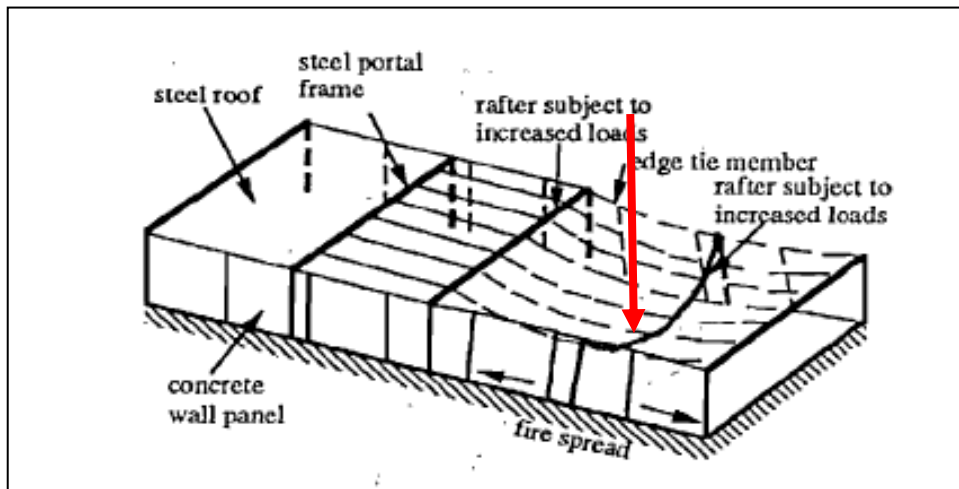


Figure 12: Isometric View of Probable Failure Mode of Portal Framed Structure.⁷ Note the addition of the probable area of origin (Red Arrow).

ABOUT THE AUTHORS

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Andrew Tinsley is a Ph.D. candidate at the University of Tennessee, Knoxville. This paper represents the beginning of his dissertation work. He is employed by Construction Engineering Consultants as a consulting engineer with areas of specialties in structural engineering, construction claims, insurance evaluations, and fire/explosion investigation. He is also an adjunct professor for East Tennessee State University, a Lieutenant at the Karns Volunteer Fire Department, and a member of the Knox County Fire Investigation Task Force.

David J. Icové, Ph.D., P.E., CFEI

Dr. David Icové is an internationally recognized forensic fire engineering expert with over 35 years of experience; Dr. Icové is the co-author of *Combating Arson-for-Profit*, the leading textbook on the crime of economic arson. He has also served as a principal member of the *NFPA 921 Technical Committee on Fire Investigations* since 1992. As a retired career Federal law enforcement agent, Dr. Icové served over his career as a criminal investigator on the federal, state and local levels. His expertise in forensic fire scene reconstruction is based on a blend of on-scene experience, conduction of fire tests and experiments, and participation in prison interviews of convicted arsonists and bombers. He has testified as an expert witness in civil and criminal trials as well as before U.S. Congressional Committees seeking guidance on key arson investigation and legislative initiative.

ENDNOTES

1. NFPA Technical Committee on Fire Investigation. NFPA 921: Guide for Fire and Explosion Investigation. 2004 edition.
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