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This chapter covers the factors that should be considered in evaluating the integrity of structures for safe use and occupancy after exposure to fire. Initially the focus will be placed on evaluating Structural Systems, and identifying the Structural Damage that may affect overall and local structural stability. In the second section of this chapter, special attention is directed to the techniques for evaluating the post-fire strengths and weaknesses of basic building materials, i.e., steel, concrete, masonry, and wood, in structural assemblies. Finally, plastics and conditions during construction will be discussed, since they present some unique problems when subjected to fire,

All structural materials, whether classified as combustible or noncombustible, inherently possess a degree of fire resistance. However, they are adversely affected when exposed to elevated temperatures during a fire. The degree of damage may vary with the different materials and building configurations. Where there is no visible cosmetic damage to the building after a fire, such as glass breakage, concrete spalling, or steel distortion, there is little chance of serious damage, although this is no guarantee. Current public interest in life safety, legal implications, and the designer's reputation require a careful inspection to verify that no further damage has occurred due to the effects of excessive expansion and hidden deterioration. A building that is "Safe" for occupancy, requires that the structural system, comprised of all of its individual elements and their connections, be able to safely support the structure's weight, contents, and environmental loads.

BUILDING TYPES

As discussed in other chapters, Model Codes classify buildings by Types (I, II, III, etc) according to their fire resistance. In general the fire resistance of the construction varies from the most fire resistant for Type I to the least for Type V, with subtypes within most categories for buildings that have more or less fire protection. Whereas, this classification system is useful in determining appropriate levels of fire protection, there may be other, more descriptive nomenclature that could better differentiate a structure's performance during and after a fire. One would be better served by a more comprehensive system for identifying structures when subjected to extreme conditions

The book, *Building Construction for the Fire Service*¹, discusses the detailed properties of the following six types of buildings.

Wood

Ordinary

Garden Apartments

Steel

Concrete

High Rise

Each has unique characteristics relative to its susceptibility to fire damage, and the challenges that it presents to fire fighting. Here one can realize the difference between a Type I Convention Center and a Type I High-Rise Office Building, with both being steel frame structures. The great variation in Wood Buildings is also partly addressed by this book.

Vincent Dunn's book, *Collapse of Burning Buildings*², addresses the collapse hazards of each of the Five Standard Types of Buildings, when exposed to fire, but also the work is expanded to cover the following:

Masonry Wall and Parapet Collapse

Wood Floor Collapse

Wood Roof Collapse, including Peaked, Flat and Timber Truss types

Lightweight Steel Roof Collapse

Ceiling Collapse

Stairway and Fire Escape Collapse

Wood Frame Building Collapse

This comes closer to addressing the need for a comprehensive guide for building performance during and after a fire. It is not a coincidence that the collapse types that Chief Dunn covers are those that have caused the majority of firefighter casualties in the recent past

ATC-20 and its companion *Field Manual, ATC-20-1, Post Earthquake Safety Evaluation of Buildings*³, presents the "State of the Art" guide for evaluating structures after devastating earthquakes. It provides detailed guidance for evaluating six types of building construction that are further divided into 13 unique structural damage patterns. These 13 Structure Types were originally presented in *ATC-21, Rapid Visual Screening of Buildings for Potential Seismic Hazards*⁴, and are referred in *NFPA 1670, Operations and Training for Technical Rescue Incidents, Appendix B*

W Wood

S1 Steel, Moment Resistant Frame (MRF)

S2 Steel, Diagonally Braced Frame (DBF)

S3 Light Metal

S4 Steel Frame with Concrete Shearwall

C1 Reinforced Concrete, MRF

C2 Reinforced Concrete, Shearwall

C3/S5 URM Infill Frame

PC1 Tilt-up

PC2 Precast Concrete Frame

RM Reinforced Masonry

URM Unreinforced Masonry

It should be understood that some buildings may have structures that have elements of more than one category, such as Wood buildings that are braced with Shearwalls and Steel Frames, or Steel Frame Buildings with Moment Frames and Diagonally Braced Frames. Also the category, "URM" usually indicates structures with exterior masonry walls and wood framed floors (Ordinary Construction).

The **ATC-20-1, Field Manual** has been especially helpful in enabling engineers to provide more consistent post earthquake evaluations, since its introduction in 1989 (just prior to the Loma Prieta Earthquake). Much can be learned from its systematic approach in providing guidelines that help differentiate between "Significant" and "Acceptable" degradation of structural systems when subjected to severe environmental loading. ATC has also published a *Field Manual for Post Flood and Windstorm Safety Evaluation of Postal Buildings*, but, unfortunately, no similar publication is available to aid in post Fire Building Evaluation. The authors strongly recommend that anyone involved in evaluating buildings after any type of event that could cause degradation should become familiar with the ATC-20 Methodology.

STRUCTURAL SYSTEMS

Every building has some sort of a Vertical and Lateral load Resisting System. Even though these systems may be poorly organized, and difficult to determine, the essential first step in evaluating any structure is to define and assess the competency of these systems.

Vertical Load Resisting Systems may be described using a Plumbing Analogy. Building loads derived from component weights, contents, occupants, etc. are collected by the smallest members in the horizontal planes, collected by beams, and delivered by columns to the foundation. The connections of all components are required to competently transfer the loads, and the failure of any member or its connection will cause a collapse.

Vertical Load Resisting Systems may be “Framed”, consisting of a coherent system of beams and columns. They may also be “Unframed” systems that have some beams and columns, but bearing walls would provide most of the vertical support. The size of the collapse will be determined by the importance of the member, or members that are compromised, and in general a “Framed” system has a greater potential for a larger collapse. These are easily understood concepts, which sometimes become lost in the chaos of a disaster situation.

Lateral Load Resisting Systems (LLRS) may not be as apparent, however. They may be described using a Pushover Analogy. The structure must have elements and interconnections that will transfer lateral loadings, acting in any horizontal direction, into the foundation system. Without a competent system, the structure will rack, i.e. rectangular spaces will become parallelograms, and possibly collapse to the ground. LLRS can be categorized as one of the following three types, or a combination of types.

Box Buildings

Moment Resistant Frames (MRF)

Diagonally Braced Frames (DBF)

The majority of buildings are **Box Type** structures. They maintain their stability by having horizontal (roof and floor) planes that should be strong, relatively rigid, and well interconnected. Plywood or solid wood diagonal sheathing on roof/floors usually performs this function in modern wood structures. Less desirable materials, such as parallel wood sheathing or 2x decking may be found in older and/or more poorly braced buildings. The floor sheathing provides lateral stability to joist and beams as well as transferring lateral forces to the walls. Wall sheathing, if adequately connected to the floors and wall structure, will keep the structure from racking as it transfers the forces to the foundation. The term “Shearwall” is used to describe a wall that has this ability to prevent racking, which may also serve as a bearing wall. Again, plywood and diagonal wood sheathing are the most desirable sheathing types, but wallboard, plaster and parallel sheathing may be the only type found on walls in marginally braced buildings. Box buildings may also be constructed with Concrete or Masonry walls Shearwalls/Bearing Walls. Also, floors of concrete or concrete filled corrugated steel decking are normally strong enough to act as “Floor Diaphragms”.

Moment Resistant Frame structures are usually constructed using Steel or Reinforced Concrete. The frames provide both vertical and lateral resistance. MRF structures require a competent floor plane (diaphragm) for lateral stability and load transfer. As previously stated, this is easily provided by a concrete or concrete filled steel floor system. The interconnection of beam and column is the most critical feature of the MRF, since in order to resist the repeated loading during high winds or earthquakes; the joints must exhibit great toughness and ductility. Prior to the 1970s, few concrete structures were capable of the required ductile performance. The 1994, Northridge Earthquake demonstrated that the, then, standard welded joints did not possess the required ductility to reliably transfer severe earthquake stresses. One needs to be aware of these difficulties when evaluating MRF structures after a severe fire. It is possible that expansion forces could cause connection damage that could be hidden by fireproofing.

Diagonally Braced Frame structures are similar to MRF, except that diagonal steel braces are strategically placed between columns to prevent racking by acting similar to shearwalls. In most occupied buildings, where rigidity is important, the diagonals are proportioned to resist both tension and compression forces. The toughness and rigidity of the diagonals and their connections are very important. Again, these members may be subjected to expansion damage during a prolonged fire. In Light industrial buildings, thin rods or small angles, capable of only tension resistance are used as diagonal braces. They need to be configured as X bracing, and need competent connections to function properly.

EVALUATING FIRE DAMAGED STRUCTURES

Evaluation of structural damage to buildings following exposure to fire needs to be undertaken at any one, or at all three time periods in the fire episode. The first would take place while the fire is still in progress, the second immediately after the fire, and the third somewhat later when the structure has been stabilized. The urgency and focus of an evaluation would be different in each of these conditions. Firefighter safety is paramount in the first instance, public safety plus adjacent structures and their occupants is the focus in the second, and safety issues involving long term occupancy is the main consideration of the final, more detailed evaluation.

When considering damage incurred from fires, it is important to take into account deterioration of structural elements, which accompany normal aging. Wood is subjected to shrinkage/drying effects, rotting due to wetting/drying cycles, animal infestations, corrosion of fasteners and the effects of poor repair and maintenance practices. Steel may have deteriorated because of inadequate corrosion protection or thermal insulation. It is not unusual to find that more than fifty percent of all buildings in urban and suburban communities are over fifty years old.

EVALUATION DURING THE FIRE

The primary purpose in this case would be to ascertain whether it is safe for firefighters to conduct control operations in or near the fire involved building. Fire Unit Commanders need to quickly assess the risk of entry versus the reward of saving lives and property. Obviously there needs to be a different equation for each. In some instances, such an early and preliminary evaluation can also be helpful in determining the necessary strategy for fighting the fire. As with all stages of structure evaluation, identification of Building Type along with Vertical and Lateral load resisting systems should be done immediately. Assessment should then be made based on a systematic approach to the problem. In some cases the choices may be very limited, as in the case in the fire at One Meridian Plaza in Philadelphia. Here, based upon inadequacy of available water supply, the decision was made to withdraw fire forces with the result that the fire burned through ten floors prior to being stopped at an upper floor by sprinklers

For incombustible and significantly fire-protected structures, the decision to enter may be made with greater confidence than other buildings. Structure collapse is usually not an immediate problem. However, in the case of steel frame structures, thermal expansion (as discussed in Chapter 4) may cause very high stresses in floor beams that are restrained by shearwalls or diagonal braces. Also expansion in unrestrained floor systems can cause the enclosing walls to become dangerously out of plumb. Thermal expansion may also cause damage in cast in place as well as precast concrete structures

At the opposite end of the spectrum, wood buildings, especially those with small member roof framing and trusses, provide the conditions that can lead to a collapse in minutes. Since these structures are relatively small and common, their performance should be well understood by most firefighting units. NFPA's Special Data Package, Firefighter Casualties as a Result of Roof or Floor Collapse in Wood-Frame Building states that in the 1980s and 90s there were 67 incidents in which at least one firefighter was killed or at least three were injured in sudden collapses. The most common collapses reported here were as a result of intense fires developing in concealed attic spaces that contained 2x4 and 2x6, supporting wood members. It should be noted that most sloped, roof wood structures with flat ceilings are framed with some sort of wood truss. These trusses may have been constructed in place in older structures or prefabricated using metal plate connectors in more modern ones, but all present a difficult problem for firefighting.

Timber Trusses have been constructed in the U.S. for more than one hundred years. They are a very efficient way of spanning large spaces, but due to this efficiency, have the potential of sudden collapse. Most roof trusses have some sort of a sloped top, compression member (Upper Chord), a level bottom, tension member (Lower Chord) and a series of interconnected diagonal tension or compression members (Webs). Flat roof and floor trusses usually have parallel upper and lower chords connected by the webs, and some sloped roof trusses (Scissors Trusses) have sloped bottom and top chords.

Prior the advent of the Glued Laminated Beam in the early 1950s, large timber trusses were used in industrial and commercial structures to span up to 100 feet and more, spaced 16 to 24 feet apart, with wood joist infilling members. These trusses were configured in a bowstring shape, or had partly sloped and partly near flat upper chords that were interconnected with steel plates and bolts (Strap and Pin) or diagonal steel rods and vertical wood posts (Rod and Block). The lower chords in these trusses are most critical since they are highly stressed in tension and interconnected by bolts. Due to normal defects in sawn timber, these bolted connections may deteriorate with time especially in hot attic spaces. They may be a disaster waiting to happen when exposed to fire, and should be approached with extreme caution when considering firefighting tactics. Fortunately, the informed observer should easily recognize structures with these trusses, and they are limited to older buildings. However a single lower chord failure could result in a large collapse.

Light Timber Trusses, spaced from two to four feet on center have also been constructed for more than one hundred years. Since the 1960s, with the advent of the metal plate connection, they have been engineered using very small wood members for maximum economy. As roof trusses they are often configured with sloped top and flat bottom (A trusses), or may be made as Scissors Trusses. When intended for floors or flat roofs, parallel chord trusses are used. Some parallel floor and roof trusses may use a combination of wood chords and tubular metal webs.

Unfortunately the attributes that make light timber trusses economical and efficient construction elements, can lead to sudden, catastrophic collapse during a fire. One has the undesirable properties of highly stressed, small easily consumed wood members that are placed in concealed spaces where fire may grow and spread between members. Collapse can and has occurred within minutes. The NFPA Alert Bulletin (97-1) states that 30 firefighters were killed in 16 incidents involving wood trusses from 1977 to 1995, and additional reports indicate that an additional ten were killed during the late 90s. The trusses spanned up to 60 feet, and most were in enclosed attic spaces. Before planning interior operations in wood structures, one must identify the type of roof and floor structures. It is most difficult to determine the presence of floor trusses, but it should be assumed that any building with a sloped roof and flat ceiling is framed with trusses until determined otherwise.

Heavy Wall Buildings present some difficult and dangerous problems for firefighters, during and immediately following a fire. These buildings are characterized as structures that are surrounded by masonry or concrete walls and are framed with wood roof/floors, and include Ordinary, URM, Tilt-up, etc, classifications. Since the walls usually act to confine the fire, the roof and floors can rapidly lose strength and collapse. Older buildings have the potential of containing deteriorated wood members, and newer, long span structures have the potential for a large area collapse. Both conditions can lead to a sudden entrapment of firefighters. The 1999 Worcester, MA fire is a tragic example of the catastrophic performance of this type of structure.

In some cases, masonry walls, even with "fire cut" ends on wood members, have been pulled in by the collapsing floors with lethal results. The potential for this type of collapse is even more probable in the western U.S., earthquake regions, since masonry and concrete walls are mechanically tied to the roof and floor structures to limit wall collapse during seismic events. Also walls can be forced outward by the ladder type forces generated when an interior collapse results in large floor or roof sections being angled up against the wall. As discussed earlier, structures of this type built prior the 1950s may have large, long span roof trusses, which may be prone to sudden collapse.

INITIAL POST-FIRE EVALUATION

Depending on the complexity of the fire, number of victims, type of collapse, etc. the Authority Having Jurisdiction (AHJ), Fire Chief or Building Official, may require that a recovery and stabilization operations be conducted. This is the essential, first post fire requirement. In cases where While building departments will normally have jurisdiction over certification of whether a building is safe for occupancy, there will be instances where the necessary technical competence and experience to conduct a post-fire investigation is not available within such agencies and here it is imperative that appropriate expert consultation be engaged.

In cases where roof and/or floor burnout have occurred, the remaining unsupported structures may require stabilization. The Public Way and adjacent, occupied structures must be protected, since heavy, freestanding exterior walls can collapse due to high wind forces. If major supporting elements have been weakened, or if parts of the structure have become misaligned, the building must be stabilized. The Vertical and Lateral Load Resisting Systems need to be identified, and significant degradation needs to be addressed. A careful, well-documented, step-by-step evaluation should be performed. One needs to identify and assess all structural systems, and provide an adequate load path of resistance for all probable environmental loadings. To accomplish this, shoring may need to be constructed and/or Safety Evaluation and Monitoring may be required.

When the fire has produced trapped victims, Recovery Operations must be allowed to proceed safely and carefully. In addition, Fire Investigators also need time to do their essential work in a reasonably safe environment. All these operations may need to be performed prior to allowing the owner's engineer and insurance investigator access. This may appear to impede their investigations, and may cause complaints to be lodged. However, safety should not be compromised at this time, If local Fire and Building Officials do not have the necessary technical competence and experience to conduct the Recovery Operations or the Post-Fire Investigation within their agencies, it is imperative that expert help and consultation be engaged. This help may be available from Federal, State or local sources.

Following the 1992 Oakland, CA Firestorm, at the request of the California Office of Emergency Services, the author performed a structural evaluation just prior to final Search and Recovery Operations at a multi building apartment project. The original 3-story wood apartment buildings built over one story, concrete parking garages had burned down to a deep pile of debris on top of the concrete structure. The parking structure was partly subterranean, and it was observed that large cracks had developed in the longitudinal, spaced shear/bearing walls of the 150-foot long structures. The 10 inch thick slab was still warm to the touch a week after the fire. It was most probable that thermal expansion had caused the cracking in the restraining walls, but that the damage was not severe enough to preclude the Recovery Operation. Since the search could be completed within 4 hours, the risk of a major earthquake that could further compromise the walls was judged to be minimal. There was no possibility of live reward, but also, there was little risk to search dogs and handlers, especially after formulating a good escape plan.

Elements of the Federal Emergency Management Agency's (FEMA) Urban Search and Rescue System (US&R) may provide assistance during this time period. This system is comprised of 28, locally based Task Forces made up of individuals with special Search, Rescue, Engineering, Communication, and Medical skills.

Immediately after the 1999 Worcester Cold Storage Fire, Search and Engineering elements from the FEMA, Massachusetts US&R Task Force I, (MA-TF-1) were dispatched to aid the Worcester Fire Department with the Recovery Operations involving the six missing firefighters. The Search element included teams of canine with handlers that were experienced in forensic and cadaver search work. They were instrumental in locating all six victims.

The Engineers deployed by MA-TF-1, known in the US&R System as Structure Specialists, provided initial analysis of the six story high, unreinforced masonry walls. They then developed a Safety Strategy for the weeklong Recovery Operation that included 24 hour monitoring of the walls and the wind speed. Recommendations for safe deconstruction of the structure to aid recovery efforts were also provided by Rigging Experts from the Task Force.

In early 2001, Structure Specialists from the Sacramento, CA, US&R, Task Force 7 provided initial evaluation of the fire situation when a large truck rammed the State Capital Building, while the legislature was in session. Fortunately, in this case, the only casualty was the truck's driver.

The FEMA, US&R System has developed, coherent emergency shoring systems that are being taught to US&R Teams throughout the U.S. The U.S. Army Corps of Engineers, through its "Readiness Support Center" in San Francisco, CA has published a *Structure Specialist Field Operations Guide* that includes information and step-by-step procedures for constructing this emergency shoring. It also includes other useful information useful during rescue situations. A printable file containing the FOG can be obtained on Disasterengineer.org

POST-FIRE BUILDING EVALUATION AND REOCCUPANCY

Most often, inspection and evaluation of fire damage would be undertaken immediately after the fire department has extinguished the fire and declared the building stable and able to safely support an engineering investigation. There is a tendency for owners to quickly remove fire debris from the scene and thereby disturb evidence of interest in damage assessment. For this reason it is necessary that cleanup and repair operations be carefully monitored and controlled while the investigation of fire damage is under way.

Some aspects of the fire damage evaluation process require that certain transient conditions regarding fire deterioration of materials regarding loss of strength be allowed to take place prior to the initiation of detailed study. This is particularly true in the case of estimating residual strength of concrete materials, which may undergo cracking, calcination, layering and discoloration in the weeks following exposure to fire temperatures.

It should also be noted that the work and reports of engineers engaged in the assessment of fire damage will often be of interest in litigations almost certain to take place following severe and high loss fires. For this reason, and in so far as is possible, methodology for conducting inspections, testing, and the manner of reporting should follow accepted practices and be fully documented. Owners or their insurance companies will normally pay for the reports and choose the engineer. However, tenants, or their legal representatives, and even the building official may also be involved in the selection process.

A detailed engineering study, will be necessary to determine the parameters for repair and/or partial replacement of the building. Damage to Vertical and Lateral Load Resistant Systems as a whole as well as individual members will need to be assessed and carefully tabulated. The determination of Significant Degradation versus Cosmetic Damage requires well-informed Engineering Judgment. A qualified Professional Engineer specializing in structures should conduct the evaluation, since the influence of distortion and residual stresses may have a significant negative effect on parts of the structure. Prudence and legal liability concerns will influence many engineers to attempt to err on the conservative side.

Insurance interests and the owner's needs for re-occupancy may argue for a greater acceptance of partly damaged structural elements. This natural conflict should be anticipated, and one may need to emphasize that since the building is being renewed, at least in part, that it needs to be at least as safe as in its pre-fire condition.

If a significant percent of the structure needs to be rebuilt, the entire building may be required to meet current building codes. Many jurisdictions have ordinances that set levels of damage that when exceeded will trigger a current code upgrade. As an example, the *1998 San Francisco Building Code* states "Repairs to structures which have sustained Structural Damage shall comply with the minimum requirements of the current code or the code under which the structure was designed, whichever is MORE restrictive". It further defines Structural Damage as follows "A structure shall be considered to have sustained Structural Damage when the vertical elements in the lateral force resisting system in any story, in any direction and taken as a whole have suffered damage such that the capacity has been reduced by more than 20 percent from its predamaged condition. A structure shall be considered to have sustained Structural Damage when the vertical load carrying components supporting more than 30% of the structure's floor or roof area have suffered a reduction in vertical load carrying capacity such that they are required to be structurally repaired or replaced in order to comply with this code." The cause of the damage for this code may be from fire, explosion, wood destroying pests, winds, earthquake, vehicular impact, or ground subsidence. It is currently contemplated that the *International Existing Building Code* will have similar requirements.

The 1994 and 1997 editions of most Model Building Codes (see Chapter 2) have requirements for "*Abatement of Dangerous Buildings*" that are less restrictive than the San Francisco Code. Buildings that are significantly damaged by fire are considered as dangerous. It should be noted that local building officials have considerable discretion in applying abatement requirements. Changed zoning requirements and economic considerations may also influence reconstruction. In most codes, buildings may be reconstructed according to prior regulations providing the cost for renovation does not exceed a given percentage of the original cost.

Historic building may be treated somewhat differently. Many Historic Buildings do not meet current codes, and if significantly damaged by fire, may not be able to be economically upgraded to current code requirements. As a result of what preservationists considered unnecessary demolition following earthquakes, a guide book, *Temporary Shoring and Stabilization of Earthquake Damaged Historic Buildings*⁵ was developed in 1998. It discusses the difficult issues facing local building, emergency, and other governmental officials regarding the saving of damaged Historic Buildings.

Finally, cooperation with the fire department is essential to establish the path and progress of fire, including the method of extinguishment. It may be possible to establish maximum temperatures reached during the fire by examining debris for melted material and by inspecting structural members for spalling, cracking, discoloration, deflection, etc.

The influence of temperature on the mechanical properties of structural materials raises the question of the "use ability" of the material after it has cooled down to ambient temperature. The evaluation of the structural behavior of steel, concrete, masonry, and wood is generally described below. A more detailed evaluation procedure and a case study of renovations is given in Chapters 12 and 13 of *A Complete Guide to Fire and Buildings*.⁶

EVALUATION OF DAMAGE TO SPECIFIC MATERIALS

The book, *Design of Structures Against Fire*⁷ contains useful information on the behavior of common building materials including structural steel, reinforced concrete, and wood when exposed to high temperatures. Of interest in this same publication is a paper on repair of fire-damaged structures that includes an assessment procedure for fire-damaged structures and a visual damage classification system for reinforced concrete elements. Also of interest to the fire investigator is the ASCE publication, *Guidelines for Failure Investigation*⁸. Here, the organization and details of post-fire examinations are outlined in enough detail to better suit the rigor of forensic inquiries.

STRUCTURAL STEEL

Thermal and mechanical properties of steel are given in ASCE's Manual of Practice entitled *Structural Fire Protection*⁹. This publication presents information on the modulus of elasticity at elevated temperatures, stress-strain curves for structural steel at various temperatures and deformation properties. Most important for evaluating load carrying capacity following exposure to fire is the loss of strength suffered as temperatures rise from about 100 to 700 degrees C. At the upper end, ordinary structural steels will lose almost all of their original strength. A second factor which influences the behavior of steel during fire incidents is the coefficient of thermal expansion which increases with increasing temperatures and reaches a value of approximately 0.008 in/in at a temperature of 600 degrees C.

The use of several grades of steel in buildings and bridges is accepted in modern building codes and design standards. Although different grades of steel have a wide range of strengths, tensile and yield strengths of all steel grades are similarly affected by the temperatures that may be expected in fires in buildings.

The behavior of beams or other members subject to bending stresses under fire conditions is complex. In a building fire, the steel temperature may vary considerably over a single cross section, as well as along the length of a structural member. Information relating to the strength properties of steel at elevated temperatures has been derived from the results of tests on small specimens heated so that the entire specimen was at or close to the measured temperature. Conclusions relating to strength characteristics from such small-scale tests may not be applicable to steel structural members. Moreover, plastic action results in the redistribution of stresses in steel members that are loaded close to the design limit. This characteristic permits steel members to sustain loads greater than those calculated to be safe on the base of yield strength alone; therefore, the strength of a given steel member cannot be determined only from isolated temperature data.

In a building fire, parts of the structure may have been exposed to heating followed by abrupt cooling by water from hose streams. This temperature change is usually less severe than what is accepted practice in heat-treating of steel during manufacture. Tests performed on structural steel specimens taken from buildings that experienced fire during and after construction have indicated that yield strengths did not drop below the specifies minimums. However, when a post-fire test is compared with the original mill tests, one can find that the original yield strength, usually at least 10% above minimum has dropped to the minimum value. This can be explained as a loss in the nominal gain in strength that occurs during the rolling process. The members that exhibited scorched paint will most often suffer this loss. It then becomes the job of the investigating engineer to determine if the loss is significant. Steel members that show some distortion due to heat, but can be straightened, should have their physical properties carefully checked. Connections between members should also be checked for cracks around fastener holes and welds.

Occasionally, steel exposed to a fire will have a somewhat roughened appearance due to excessive scaling and grain coarsening. The coarsening is caused by exposure of steel to temperatures around 1,600°F (870°C) or higher. The steel will usually have a dark gray color, although other colors may be present if certain chemicals have been involved in the fire. Steel so modified is commonly called "burnt" steel. Members that have become burnt will usually be severely corroded as well, and their suitability for further use is a matter for individual judgment.

Some instances have been reported where straightening of structural steel members distorted due to fire has been both feasible and economical. Following the McChord Air Force Base fire in 1957 near Tacoma, WA, in which two aircraft hangars were seriously damaged, 1,486 structural steel members were either straightened or replaced in the steel frame. Of that number, only 46 members were replaced; the remaining 1,440 members were flame straightened, using welding torches.

CAST IRON

The use of cast iron as structural material has all but ceased. If found, these buildings are undoubtedly archaic, historical preservations. A number of such buildings may still be found in New York City and elsewhere. In some instances only the facades are of cast iron, in other cases both the structural elements and facades are of this material. The behavior of cast iron when exposed to fire temperatures is substantially different than steel. Cast iron exposed to temperatures of 800 degrees F (427 degrees C), will deteriorate and fracture if struck with water from a fire hose.

PROTECTIVE COATING ON STRUCTURAL STEEL

Excluding fire protection features, such as extinguishing systems, low fire loads, compartmentalization, etc., damage to structural steel members may be minimized by application of protective coatings that provide a period of fire resistance. Generally, a fiber or cementitious mixture is applied by spray application; however, the adherence and durability of such coatings, even under normal circumstances, has been the subject of some concern. Too often, questionable application resulted in unreliable fire resistance and, subsequently, considerable structural damage.

A large fire in a 50-story office building known as One New York Plaza occurred in 1970 in New York City and resulted in three fatalities. Much of the ten million dollars in physical damage arose from failure of sprayed-on thermal insulation. This incident was instrumental in the passage of New York City's, Local Law Number 5 that is a comprehensive approach to improving life safety in High-Rise office buildings.

Sprayed-on protective coverings can be expected to be easily dislodged during fire fighting and overhaul operations. Usually problems of this kind are easily detected, but a complete examination of the structure must be made to determine the extent of damage. Also, before occupancy is permitted, it is imperative to determine that fire damage to a specific section of a building does not impair the integrity of zones of safety, means of egress, and smoke towers, or the operation of fire doors, fire dampers, or other protective devices or systems in areas not damaged by fire.

FIRE TESTS

Unfortunately, many architects and design engineers are of the opinion that the ASTM E119, *Standard Test Methods for Fire Tests of Building Construction and Materials*, fire-resistance test provides factual data of materials and assemblies under actual fire conditions. At best, it is a destructive comparative test with little relation to actual fire.

Heavy damage to roofs, floors, beams, and trusses has been traced to misinterpreted fire test listings. For fire-resistive purposes, many floor/ceiling and roof/ceiling assemblies are considered as a single fire-resistive element. The ceiling by itself does not provide a specific fire-resistance rating. It should be noted that many floor or roof and ceiling tests provide an assembly rating, as well as a beam rating. Untrained persons have assumed the beam rating as protection afforded by the ceiling. Unfortunately, since the ceiling membrane does not provide a fire-resistance rating, structural components above the ceiling are subject to damage.

CONCRETE

In a fire lasting one to two hours, concrete will be generally only moderately damaged, and so routine cutting and patching procedures will usually be adequate before repairs. In intense and lasting fires, such as those, which may occur in large, heavily stocked warehouses and department stores, severe damage to concrete may be expected. In some cases of record, restoration entailed the removal of severely damaged areas and patching in areas less severely damaged. Experienced engineering judgment is required for evaluating the residual strength of those areas that are somewhere between moderately and severely damaged. An example of one approach to the problem of evaluating the residual strength of apparently marginally damaged concrete structural units can be found in the article "Prestressed Concrete Resists Fire."¹⁰

Over the past two decades much progress has been made in the improvement of methods for analysis of properties and behavior of concrete exposed to elevated temperatures. Included in the technology are full scale test results, model studies and analytical methodologies directed to long standing issues including: influence of restraints on reinforced concrete columns, deformation behavior and thermal damage. These developments offer valuable tools for estimating the extent of fire damage and residual strength following fire exposure of structural elements and systems. *Fire Safety Design & Concrete*¹¹, discusses Structural Response of Concrete Elements to Fire. This work presents basic engineering concepts for considering flexural elements, compression elements and complex structures and frames.

The use of admixtures to produce various desired characteristics in concrete has increased over the years. There are now on the market dozens of products for strength enhancement, set acceleration and

retardation, shrink reduction and flowability, early strength, reduced permeability and other qualities. Long-term effects of some of these additives on strength and durability are not well researched and the same is true for behavior of these concretes during and following exposure to fire conditions.

With the increasing use of high performance concrete (HPC) with compressive strengths exceeding 16,000 psi, the matter of spalling at high temperatures has become of interest. Research in the U.K. [12,13] and elsewhere indicates that “explosive spalling” greatly reduces the fire resistance of concrete and that increasing the strength of concrete can be expected under certain conditions to reduce fire performance. The identification and control of unfavorable factors such as curing and drying conditions, aggregate size and type and concrete permeability is currently under investigation. Work on the characterization of High-Performance concrete is underway at the National Institute of Standards and Technology (NIST) using quantitative image analysis to determine the macro and micro-structures of HPC in relation to the response to fire.

A waiting period of perhaps several weeks should elapse after the fire has been extinguished before careful study of structural damage is initiated. This delay will allow any damage to the concrete, such as cracking, layering, calcination, and discoloration change from the natural gray color to pink or brown is indicative of heating to temperatures in excess of 450°F (232°C)], to become more discernible. The thickness of fire-damaged concrete in structural members can be determined by chipping with a pick or geologist's hammer. Unsound concrete may be colored and will be more or less soft and friable, while sound concrete will give a distinctive ring when struck with a pick or hammer. Cored concrete samples for compressive strength tests and reinforcing steel for tensile strength determinations will enable a closer evaluation of the residual strength of damaged members. Load tests may be applied, but should be conducted only under the supervision of a registered structural engineer.

Two other methods for evaluating fire damage are worthy of mention, but each requires an experienced operator. These make use of the Schmidt hammer and the soniscope. The Schmidt hammer has a spring-loaded plunger, which is caused to strike the test surface by the release of a trigger. The rebound of the plunger is a measure of concrete strength. The rebound numbers should not be considered more than a qualitative evaluation of the concrete strength, as there are several variables other than strength that may affect rebound numbers. The soniscope is an electronic device that has been used to gage the soundness of relatively heavy concrete sections, such as highway pavement slabs, bridge components, and dams. A high-frequency pulse is directed by an electronic sender through the section in question and is picked up by an electronic receiver. The speed at which the pulse travels through the section from sender to receiver, in feet or meters per second, is a gage of the integrity of material in the pulse path. Severe exposure of heavy concrete sections to fire may cause “layering,” i.e., partial separation of the outer 1 to 2 in. (25.4 to 51 mm) of concrete of a building member from the interior mass. Such “layering” can absorb the full energy of the pulse, so interpretative experience is necessary. The device has been successfully used in conjunction with other methods in at least one case to evaluate fire damage.

A complete report dealing with a survey of fire damage to a multi-story reinforced-concrete building and the subsequent repair procedure can be found in the paper *Fire Damage to General Mills Building*.¹⁴

REPAIR OF FIRE DAMEGED CONCRETE

A severe fire occurred in 1951 in an unsprinklered paper warehouse. This fire lasted for more than 44 hours, and it is estimated that heat intensities of more than 1,600°F (870°C) existed for 3 hours or longer. Even after severe fire, the structure was still standing and the concrete floors prevented the spread of fire and major water damage. An inspection of the structure after the fire showed that the concrete roof and columns appeared to have suffered little damage, except that the roof showed deflection up to a maximum of approximately 2½ in. (64 mm) in a 20-ft (6.1-m) span. When holes were cut through the roof, it was found that the concrete was calcined and had a light brown color in varying depths. This damaged concrete had almost no strength and began to disintegrate after a period of several weeks. As a result, the portions of the roof slab that showed appreciable amounts of calcine were replaced. Many of the columns required removal of the concrete down to the reinforcing steel spiral, and, in some cases, calcining appeared inside the spiral. In these cases, the entire column was replaced. The column caps were replaced completely if more than one-half of the column showed evidence of calcining. Reinforcing rods showed some reduction in tensile strength, but most were salvaged and reused and downgraded to about three-quarters of their original strength.

In 1982 a fire-damaged rapid transit terminal in Chicago was scheduled for demolition. Due to the inflated cost of rebuilding and time lost, a cost-effective study suggested restoration. The \$18.4 million building was restored at a cost of \$200,000, and a minimum of time.

If a decision is made to repair the damage, the usual procedure is to shore up the structure, if necessary, and to remove the fire-damaged concrete, using a hammer, chisel, or a lightweight mechanical hammer. (Use of heavy hammers is discouraged, since they might aggravate the damage by inadvertently chipping good concrete.) The steel reinforcements are then cleaned and, if necessary, additional reinforcements are added and, finally, the concrete is built up with air blown grout. Durable concrete repairs also have been made with epoxy resins.

The significant difference between conventional reinforced concrete and stressed concrete in fires is the performance of the high-tensile-steel wire or rods used for pre- or post-stressing. Under fire conditions, the stressed steel units are liable to rapid loss of strength at temperatures in excess of 752°F (400°C). A load test is recommended in post-inspection for significant pronounced sag or an indication of excessive temperature in a range where stress loss may have been sufficient to seriously affect the strength.

Tilt-up construction is a popular, simple, and effective type of concrete construction. As the name implies, slabs are site, precast adjacent to their final location, and lifted into place. In older structures, dating from the 1950s & 60s, the reinforcing steel projecting from adjoining wall panels was encased in cast-in-place concrete columns. These systems provided relatively reliable fire resistance. In more recent construction, the wall panels are connected by exposed steel weldments, which are vulnerable to fire damage. The joints in this type of newer "value engineered" construction are filled with flexible, combustible mastic instead of concrete.

Also Tilt-up construction does not normally allow the walls to be as well connected to the foundations as in normal cast-in-place construction. This can result in an even more potentially dangerous condition when the roof has been burned away. The, then, unsupported walls are quite vulnerable to tip-over in windy conditions. The San Francisco Building Code requires that this and similar "Heavy Wall" buildings be designed for "Burn-out" conditions, and more competent wall-foundations are required. One should be especially aware of this inherent weakness, during and immediately after a fire.

Several fires on the West Coast have displayed these inherent weaknesses. Complete collapse and highly damaged panels precluded any effort of cost-effective repair.

BRICK

During production, clay bricks are exposed to temperatures in excess of 2,000°F (1093°C), hence their strength is retained in actual fires. Reinforcing steel embedded in the center of a clay brick wall would normally be protected by a minimum of 3 to 4 in. (76 to 102 mm) of brick and not be affected. Spalling should be expected, especially if hot bricks are drenched with water from a fire hose. In most cases, temporary repairs can be made with epoxy cement or air blown grout. Permanent repairs are more appropriately made by replacement, in kind, of the defaced brick.

WOOD

Wood is one of the oldest and most widely used building materials. Its behavior in fire conditions varies considerably, depending upon the species of wood and the design configuration, i.e., solid sawn lumber, glue laminates, plywood, wood chipboard, etc. The effect of fire on glue laminates may be considered the same as that on solid sawn lumber (heavy timber), assuming that the adhesives used were not affected by heat and that metal plates joining members and their attachment are not damaged. Generally, the phenol-resorcinal and melamine adhesives are not affected by heat. Plywood and chipboard are also dependent upon proper adhesives, the difference being slow burning versus a hazardous flash fire caused by delamination.

There are two primary aspects of the behavior of wood materials exposed to fire and other sources of ambient heat. The first involves loss of strength as a result of burning away of material. The second is its contribution to the energy released in a fire through its combustion. Time rates of loss of material and strength can be estimated in terms of char depth and direction of fire spread can be estimated by developing char depth contours. This was the procedure used to trace the extension of fire in the Happy Land Social Club that took 87 lives in New York City in 1991. Ignition temperatures and contributions to heat release in a specific fire depend upon a number of factors including: species, density and moisture content. Long term exposure of wood to elevated ambient temperatures reduces strength and lowers ignition temperature. Both of these effects can be important in the overall investigation and evaluation of structural damage from fire.

The notching of wood structural members can also play an important role in determining the time for failure and estimation of residual strength of structural timber constructions. The practice of undercutting

of wood beam-ends can also cause problems during fires. Here, the inverting of these members on reuse reduces the bearing area and can contribute to early failure and collapse.

ASCE's *Guide and Commentary for the Evaluation, Maintenance and Upgrading of Wood Structures*¹⁵ provides detailed information on serviceability factors, inspection, evaluation of load-carrying capability of timber structures and methods of repair.

Redwood, found on the west coast of the United States, withstands high fire exposures. It is reported that the high resistance is due to the lack of the usual volatile resins and oils found in other woods. Redwood forests have resisted fire for centuries.

When wood structural members are subjected to fire, the ability to withstand the imposed loads is dependent to a degree upon the remaining undamaged cross-sectional area. The average rate of penetration of char when flame is impinged upon an exposed wood member is approximately 1 1/2 in. (38 mm) per hr. Beyond the char area to a distance not more than 1/4 in. (6 mm), the structural properties of wood may be affected by its exposure to high temperatures. The degree of strength loss in this small zone adjacent to the char is not exactly known but is presumed to be insignificant.

Fire tests made on two solid sawn wood joists, 4 by 14 in. (102 by 356 mm), nominal size, at the Southwest Research Institute showed that, after 13 min. of fire exposure, 80 percent of the original wood section remained undamaged and available to carry the load.⁶ In another test of two 7- by 21-in. (178 by 533 mm) glued laminated beams, after 30 min. fire exposure, 75 percent of the original wood section remained and continued to support the design load.¹⁶

The previous tests, as well as actual fire experience, substantiate the fact that large-dimension wood members will remain in place under fire conditions and continue to support design loads. It is usually in the larger or heavy timber members that char can be scraped clear and an evaluation made by a qualified engineer or architect to determine the remaining load-supporting capacity of the wood member. As previously discussed, trussed wood roof structures constructed with 2x4 and 2x6 members, have a history of lethal, sudden collapse, when exposed to fire.

The practice in older, wood frame buildings was to diagonally cut the tops of wood beams within the bearing wall pocket so that in the event of failure due to fire, the weight of the member would not tear out the wall masonry and/or cause collapse. Further, on reuse of older wood beams it was the practice to invert the beam which then placed the cut in the pocket resulting in a reduced bearing area and ability to take shear load. Because of the large number of wood framed buildings in existence, the condition of floor and roof beams at bearing walls should be carefully examined following exposure to fire.

Unanticipated problems often arise following building conversions and other structural and spatial renovations which may conceal spaces which were originally open, or expose spaces and structural members which were originally concealed and protected from fire. The latter can be particularly hazardous in un-sprinklered buildings.

A good example of the complexity of restoration work following a fire is described in the paper *Saving the Exeter Street Theater*¹⁷. This landmark building in Boston, MA was constructed in 1885 and ravaged by fire in 1985. One of four, eighty feet long, 18 feet deep wood trusses and the roof were severely damaged. Besides preserving the original character of the building, engineers were obliged to meet structural requirements of the modern building code. Among other conditions, designers were faced with serious truss decay at the bearing locations and the top and bottom chords were distorted and had shrinkage defects. Restoration efforts plus changes in the useable spaces in the building required use of a full range of structural technology and illustrate the importance of careful evaluation of all aspects of wear and aging in addition to fire damage which must be addressed when older buildings are involved. The special case of evaluating and predicting possibilities for collapse while a fire is still in progress is of interest to fire forces engaged in rescue and fire control operations. Here there is need for the evaluator to recognize early signs of impending failure of both structural and non-structural elements and systems. Failure resulting in collapse of ceilings, sheathing, glass and other elements of construction which do not directly affect structural integrity may endanger firefighters and also contribute to the growth and extension of fire.

PLASTICS

Plastic construction is limited to small structures, student housing domes, cabins, and radomes. The use of plastics in buildings has steadily increased,⁸ as well as the resultant fire load. The Munich Reinsurance Company reported extensive losses due to corrosion from gaseous decomposition of burning plastic. Twelve buildings were listed as having extensive corrosion-damaged structural steel members. In several cases, it was necessary to destroy the buildings. Steel members moderately damaged by corrosion may be sandblasted, but it is suggested that a stress analysis be conducted before repairs are started. Damage to reinforcement concrete is more complex, since corrosion, in time, is apt to penetrate to the reinforcing. Preliminary analysis is necessary before power hammers are used to inspect extent of damage to reinforcing steel.

FIRE DURING CONSTRUCTION

A dangerous practice is often found during the course of construction of steel-frame buildings. It is common during the application of fireproofing to structural steel members that the coating on the lower first and second stories is postponed until final stages of construction. The application of fireproofing to these lower floors is often delayed due to the potential damage in these high-traffic areas. These are the heavy-working areas and contain storage of materials and equipment, much of which is highly combustible.

Buildings of reinforced concrete depend upon wood shoring supports to retain the shape of the building until final curing time. As above, at this stage of construction the building is highly vulnerable to fire damage.

An extreme example of this problem was demonstrated by the St. Mary Cathedral in San Francisco, CA, built at a cost of \$10 million to replace a former church destroyed by fire. The cupola walls extended some 150 ft (46 m) above the ground floor. The supporting scaffolding filled the interior with 1¹/₂ million board feet of lumber at a cost of \$100,000. The chief building superintendent, aware of the fire loss potential, ruled that a temporary sprinkler system be installed.

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