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In This Issue:

A Tribute to Dr. Robert White

In The Next Issue:

U.S. Research on Cross-Laminated Timbers

Editorial

This issue of Wood Design Focus is dedicated to the late Dr. Robert White. Robert's research significantly impacted fire and safety standards of building materials used in construction. Throughout his career, Robert had considerable involvement with ASTM International, chairing and serving on numerous committees that establish building code standards. He was an internationally-recognized expert on regulatory fire resistance tests and fire performance of wood products. Robert was as genuine as they come. He was best known for his meticulous attention to detail, scientific integrity and sense of humor.

The first article is a tribute to Robert's career at the Forest Products Laboratory. It highlights some of his major accomplishments including increasing the understanding of charring of wood, structural fire resistance of both solid sawn and engineered wood, development of the room corner fire test and the fire performance of wood-plastic composites. His contributions advanced the fundamental understanding of the fire performance of wood products and increased their use in the built environment.

After exposure to fire, a structural evaluation of charred heavy timbers should be conducted to determine if the timbers are safe for future use or if repairs are required. In the second article, a sequence of steps are presented that layout how to analyze charred timbers and obtain the information needed to determine if the charred timbers are structurally acceptable based on the applicable building code.

Robert researched utilizing wood-based paneling as thermal barriers. The third article provides an introduction to using wood coverings to provide fire protection of underlying products. The low thermal conductivity and slow charring rate of wood products can protect underlying products from being heated and ignited. An extensive test program was performed according to the new European system which showed that wood-based and solid-wood panels and cladding can meet the requirements of K Class. The article presents information on the panel thickness and mounting conditions necessary for wood products to achieve K Class.

Robert's recent collaboration with FPInnovations focused on developing the fire chapter of the 2013 U.S. Edition of the Cross Laminated Timber (CLT) Handbook. The fourth article provides an overview of some of the most current CLT fire research including the fire resistance of CLT assemblies and a CLT-concrete composite floor, flame spread ratings, fire stopping issues, and real-scale fire tests. Research of this nature will further advance the use of CLTs in construction.

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Improvements to the Understanding of the Fire Performance of Wood over the Past 30 Years - A Tribute to Robert Hawthorne White

Samuel L. Zelinka, Mark A. Dietenberger, Laura E. Hasburgh, Keith J. Bourne, and C.R. Boardman

Abstract

Dr. Robert Hawthorne White had a 31 year career researching the fire performance of wood and wood composites at the USDA Forest Products Laboratory. Over his career, Dr. White made substantial contributions to codes, standards, and regulations pertaining to the design of wood structures. This review article summarizes Robert's major accomplishments as a tribute to his career at the Forest Products Laboratory.

Introduction

Robert Hawthorne White began his career at the USDA Forest Service, Forest Products Laboratory (FPL) in 1972 as a summer intern while obtaining his undergraduate degree from Pennsylvania State University. He returned to FPL after completing his M.S. in Forest Products at Oregon State University. He began his formal research career at FPL in 1980, while simultaneously pursuing his Ph.D. at the University of Wisconsin, Madison, which he obtained in 1988. Over his research career, Robert published over 120 technical papers and gave 58 scientific presentations (of which 23 were invited). Additionally, he made substantial contributions to ASTM standards on the fire performance of wood materials through his work on ASTM International (formerly known as the American Society for Testing and Materials) committees E5 (fire) and D7 (wood).

Concurrent with Robert's career, our knowledge of the fire performance of wood and wood products has greatly changed in the past 30 years. This paper highlights Robert's contributions to the current understanding of fire in wood products, especially his contributions to the fundamental understanding of char formation and structural fire performance of wood. Robert's major scientific accomplishments are summarized below in roughly chronological order.

Dr. Robert H. White

KEYWORDS : *Wood, Char, Fire Resistive Coatings, Fire Resistance*

Fundamental Studies of Char in Wood

One of Robert's first and most important accomplishments was his contribution to the understanding of the development of char in wood. When wood is exposed to high temperatures, it decomposes into char. Char is thermally insulating and helps to protect the remaining wood material from damage. The rate of char formation determines how fast the wood member is consumed in a fire and how fast the load bearing capacity of the wood is reduced during a fire. Throughout his career, Robert made notable advances in how we understand the kinetics of char formation and destruction in wood under different fire exposure conditions, notably the ASTM E119 time-temperature profile (Anon 2014).

An early influence on Robert's career was Dr. Erwin (Erv) Schaffer. Robert's early work in collaboration with Erv focused on expanded charring models to include two factors; the recession of the char layer on the outer surface of the material and the role of moisture movement and vaporization in the charring process (White and Schaffer 1978; White and Schaffer 1981). Their work showed, for the first time, that the char layer receded because of shrinkage, rather than further oxidation or ablation. To study the role of moisture movement, Robert instrumented wood exposed to fire with electrical resistance moisture meter probes and developed a moisture meter temperature correction for extreme temperatures. Through this study, he was able to show that the predominant mode of moisture transport was caused by a pressure gradient in the wood caused by the vaporization of water (as opposed to a moisture gradient or temperature gradient, which are the predominant driving potentials under most conditions). This pressure gradient causes a peak moisture content to form in the wood near the char-wood interface. The peak moisture content can be as high as twice the starting moisture content of the material.

Prior to Roberts's research, a simple linear model was frequently used to describe the growth of the char layer in wood. However, his accomplishments in this area led to the development of a more accurate, non-linear char rate model for wood. Both the Eurocode and the National Design Specifications for Wood Construction (NDS) now incorporate a non-linear char rate model in their calculations of the passive fire resistance of wood members.

Fire Resistive Coatings

In the early 1980s engineered wood building products such as glue-laminated beams, trusses and wood I-joists were gaining in popularity, and a need to improve the fire resistance of these products became apparent. At that time, Robert noted that while there were many fire retardants available for wood, they were designed to limit ignition or flame spread on a wood product and offer little fire resistance in a post-flashover scenario. He instead suggested that fire resistive coatings might be better suited to improve the hourly fire ratings of engineered wood products. At that time, there were no commercial fire resistive coatings for wood, although such coatings had been developed for steel members and foam plastics. Robert designed a study that evaluated four fire retardants and four fire resistive coatings (originally developed for steel and plastic) on plywood panels and subjected them to the ASTM E119 time-temperature profile (White 1983; Anon 2014). The results of this study showed that even though the fire resistive coatings were not designed for use on wood, some added as much as 40 minutes of fire protection when compared to an unprotected plywood specimen. These early results suggested that 1-hour, or potentially 2-hour, fire rated assemblies may be possible in a fire resistive coating specially developed for engineered wood (White 1986).

Following these promising early results, the National Fire Protection Association (NFPA) suggested that the FPL hold a workshop on the future of fire resistive coatings. This workshop was held in the spring of 1988 and included representatives from the wood products industry, coating manufactures, test laboratories and insurance companies (White 1989). This workshop along with Robert's earlier work on fire resistive coatings for wood sparked a new area of research. Today, there are several commercial fire resistive coatings formulated especially for engineered wood that can reach 1-hour or 2-hour fire ratings.

Structural Fire Resistance

As a graduate student, Robert started his scientific career researching char rates among various species of wood and what caused differences in those char rates. He then built upon this research to develop a model for calculating the fire resistance rating of solid-sawn structural members as a function of char rate. This research directly impacted the code acceptance of fire-resistance calculation procedures for determining fire resistance of structural wood members. His extensive knowledge in structural fire resistance of wood products led to many collaborations and several studies including, but not limited to, the fire resistance of both composite materials and trusses.

In the 1970s, composite lumber products began with the creation of laminated veneer lumber (LVL) which continued with parallel strand lumber (PSL) in the 1980s and laminated strand lumber (LSL) in the 1990s

(Yeh 2003). When composite lumber was first considered for use in buildings, questions regarding fire resistance and structural performance after exposure to a fire were raised, specifically due to the performance of the adhesives at high temperatures. Robert conducted several tests on LVL, LSL and PSL to determine the char rate and their performance when loaded in tension while subjected to the ASTM E 119 fire exposure in an intermediate-scale horizontal furnace (Anon 2014). His findings showed that the char rates for composite lumber products were comparable to those of solid-sawn lumber, resulting in the use of the fire-resistance calculation procedures for solid-sawn lumber to estimate the ratings of composite lumber products. Today, the National Design Specification/Technical Report 10 includes procedures for calculating fire resistance ratings of structural composite lumber.

In the early 1990s, Robert collaborated with Dr. Steven M. Cramer (University of Wisconsin, Madison) to evaluate and develop a numerical model that could be used in understanding and evaluating the fire endurance of truss assemblies. The developed fire endurance model can be used to predict the failure time of metal-plate-connected wood trusses exposed to a design fire. The model also calculates deflection, forces within the members, and mode of failure which allows designers in the truss industry to examine the predicted performance of a truss design at high temperatures before proceeding with an ASTM E 119 test (White et al. 1993; Shrestha et al. 1995).

Development of the Room Corner Fire Test in the United States

In the 1980's room corner fire testing was in its infancy and there was no formal ASTM standard. The FPL room corner fire test using the oxygen consumption method to measure the heat release rate was developed by Dr. William Parker from the National Institute of Standards and Technology (NIST), Dr. Marc Janssens from the American Wood Council, and FPL employees John Brendan, Dr. Hao Tran and Sue LeVan. In 1991, Robert began work on the room corner fire test and collaborated with Dr. Mark Dietenberger, Dr. Marc Janssens and Dr. Ondrej Grexa to examine the European version of the room corner fire test, ISO 9705 (Anon 1993).

Robert and his cooperators showed that, in certain cases, the ISO 9705 method could be used to assess the flame spread index of certain materials such as wood, wood-based materials, Type X gypsum board, and fire retardant treated polyurethane foam and give results consistent with the ASTM method for determining the flame spread index, ASTM E84 (White et al. 1999; Anon 2015). However, for other materials and other test configurations allowable under the ISO 9705 method, the ISO method did not correlate with the ASTM flame spread index. In further testing on matched samples, they were able to develop fire growth models to predict time to flashover and ASTM E84 flame spread index data from cone calorimeter data (Dietenberger et al. 2012; Grexa et al. 2012). Additionally, Robert helped in the development of creating an ASTM analog for the ISO 9705 method through his work with the ASTM E05 task groups.

Fire Performance of Wood-plastic Composites

Robert began a long collaboration with Dr. Nicole Stark, Research Chemical Engineer at FPL to investigate the fire behavior of wood-plastic composites. Early work was motivated by the desire to increase markets for recycled plastic by mixing with wood products and focused on effects of different amounts of plastic (Stark et al. 1997). The methods and research tools used to characterize fire behavior were still in flux at that time, so the first tests were done with the Ohio State University rate of heat release apparatus. Small samples were exposed to a steady heat flux and source of flame until they ignited. The rate of heat release (HRR) was determined by the newly developed method of oxygen consumption and plotted over time. In general, composites with higher plastic content had higher HRR and, hence, reduced fire performance compared to wood.

Later work on wood-plastic composites used the cone calorimeter; a standard tool and set of methods for investigating the fire behavior of materials using a small (10 cm x 10 cm) sample. Many different studies were carried out, eventually producing a dataset of the test results for a variety of materials. Typical of these results was work done on wood-based decking material (White et al. 2007). Motivated by the desire to address fire concerns in the wildland-urban interface a series of cone tests evaluated three different classes of material: southern pine lumber, naturally durable species, such as redwood, and wood-plastic composites. Results included not only the HRR, but also time to sustained ignition, and total heat released, which help to further characterize the fire behavior. These data were used to try to predict the flame spread index that determines the fire class.

Given the generally reduced fire performance of wood-plastic composites there has been on-going interest in use of fire retardant additives. Robert and Nicole published results characterizing five different additives mixed into wood flour-polyethylene composites (Stark et al. 2010). This represents one of Robert's most cited papers. Magnesium hydroxide increased ignition time, while ammonium polyphosphate resulted in reduced heat release rates.

Broader Impact and Concluding Remarks

Robert was internationally-recognized by colleagues and mentored numerous scientists and students from all over the world. His research has had a major impact on establishing safety standards of building materials used in construction. He often mentioned that one of the best parts about working at FPL was that, as a federal researcher, all of his data and publications were in the public domain and freely available to other scientists and the public. Both Chapter 18: Fire Safety of Wood Construction from the Wood Handbook and Analytical Methods for Determining Fire Resistance of Timber Members from the SFPE Handbook of Fire Protection Engineering are just two examples of Robert's impact on a wide variety of audiences (White 1995; White and Dietenberger 2010). His papers have been cited over 1,500 times. Additionally, Robert worked with the American Wood Council to develop the cone calorimeter database. The database, created in 2010 to increase the availability of cone calorimeter test data files to the public, has been downloaded more than 150,000 times to date.

Throughout his career, Robert had considerable involvement with ASTM International, chairing and serving on numerous committees that establish building code standards. Robert served as chairman of Subcommittee E05.21 on Smoke & Combustion Products and also of Subcommittee E05.22 on Surface Burning. In 2007, he received the L.J. Markwardt Award for his notable contributions to the knowledge of wood as an engineering material. In 2009, Robert was presented with an Award of Merit and an honorary title of Fellow for recognition of his outstanding contributions to the development of ASTM standards. Robert was also a member of the Forest Products Society, the National Fire Protection Association, the International Association for Fire Safety Science and the International Union of Forest Research Organizations, where he served as deputy coordinator for the wood protection research group.

He was a university lecturer, graduate student advisor, counselor to local fire departments, host to international visiting scientists, advisor to Underwriters Laboratories (UL), and served as an expert witness. He will always be remembered for his unparalleled integrity, dedication to the Forest Products Laboratory and the wood products industry as a whole, and his contributions in advancing the fundamental understanding of the fire performance of wood products.

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Post-Fire Analysis of Solid-Sawn Heavy Timber Beams

Robert H. White and Frank E. Woeste

Introduction

After fire exposure, design professionals are sometimes called upon to determine if the charred heavy timbers (Figure 1) are safe for future use without additional support or repairs. In this article, the authors present a sequence of reasoned steps that will help design professionals analyze charred timbers and gain the type of information needed to decide whether the charred timbers are adequate based on the applicable building code.

Case Study

In the example case, the initial available information is as follows:

1. Timber floor beams appear to be nominal 12x16 surfaced 4-sides southern pine.

2. The client believes the typical char depth is about ½ -inch.

3. No evidence exists that the timbers were graded.

Often, in older buildings, timbers are not "grade marked" and there are no records of any grading of timbers at time of construction.

Recommended Steps for Analysis

What follows is a series of recommended steps for analysis of charred timbers. This approach should allow a registered design professional to determine the adequacy of post-fire timbers to carry structural loads. For example, Figure 2 shows a beam in a renovated textile mill that was constructed in 1850. The timbers are valuable and replacement would be extremely costly in the event of a fire event. Replacement of the timbers may not be an economically option, thus an in-depth structural engineering analysis, post-fire timber evaluation, and code-conforming re-design could establish that the timbers could be saved for future use.

KEYWORDS : *Fire, Heavy Timber, Post-Fire, Wood, Lumber*

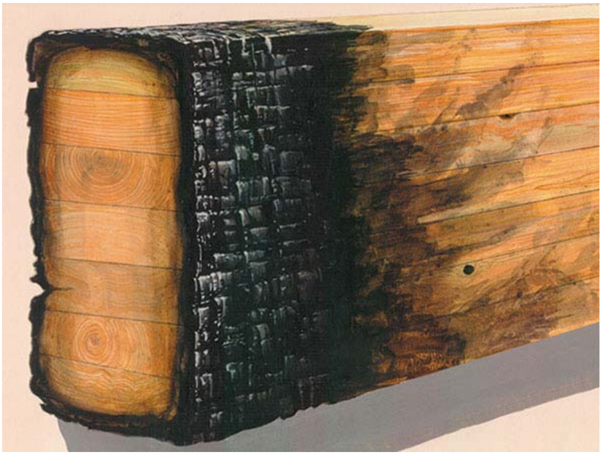

Figure 1. The Evaluation of a Glued Laminated Timber or Other Structural Composite Lumber Will Require Considerations of Factors Beyond Those Discussed In This Article

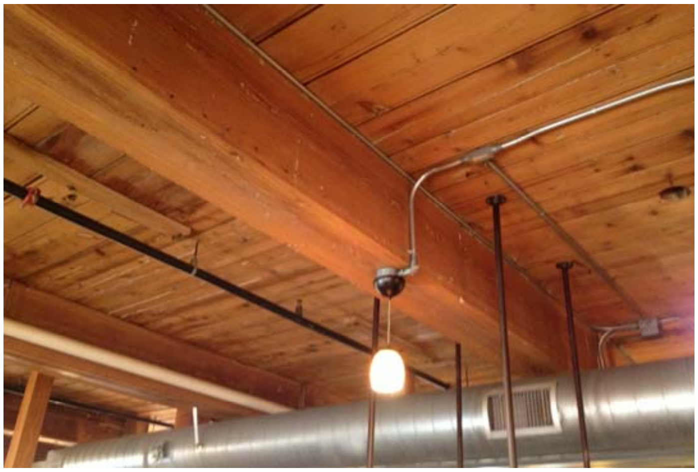

Figure 2. Large Timber Ceiling in Renovated 1850 Textile Mill

Step 1. Feasibility "Paper" Study

First, the registered design professional (RDP) can conduct a feasibility "paper" study to initially determine if the residual cross sections of the charred beams have a reasonable chance of being adequate under current code loads and other loads deemed to be appropriate by the RDP.

By assuming reference properties listed in the National Design Specification® (NDS®) for Wood Construction for a new No. 2 Southern Pine timber (nominal 5x5 and larger) since this is a common grade used, and by reducing the cross-section based on initial estimates of the char depth. The charred layer is assumed to have no residual strength and stiffness.

Based on the outcome of the paper study, the RDP and client can make a decision to move forward as discussed in the next section, in lieu of replacing the timber outright.

Step 2. Preliminary Investigation of Timbers using a Limited Sample of Char Depths

In this step, calculations are refined by more accurate measurements of the dimensions of the charred beam and consideration of thermal damage to the uncharred wood. In a typical fully developed fire, the base of the visible char layer will reflect a temperature of approximately 550°F. Depending on the intensity and duration of the fire exposure, a zone or layer of wood beneath the char layer experiences some irreversible loss in load capacity. While days of heating at 150°F can have a permanent effect on mechanical properties, the temperature effect on mechanical properties is reversible for heating periods of hours at temperatures below 212° F. From temperatures of 390°F to 570°F, the wood components of hemicelluloses and lignin begin to undergo significant degradation. Significant depolymerization of the cellulose component of wood occurs between 550°F and 660°F. Thus, the zone beneath the char layer between 212°F and 550°F has the potential of irreversible loss in mechanical properties due to thermal degradation.

Effects of elevated temperatures are primarily on the strength properties. The effect on stiffness is considerably smaller. In addition to temperature, adverse effects depend on duration and type of exposure. In contrast to the impact on strength properties of wood at elevated temperatures, the loss in tensile strength after cooling to room temperature is greater than the loss in compressive strength.

Since wood is an insulator, the temperature gradient in the cross-section is typically fairly steep during a fully developed fire (Figure 3). In heavy timbers subjected to fire exposure of the standard fire resistance test (ASTM E119), the 212°F temperature location (or front) will be approximately 0.5 inch inward from the base of the char layer after the first 15 or 20 minutes of fire exposure. In an actual fire, the temperature profile within the wood section will depend on the severity and duration of the fire exposure and post-fire exposure. One can account for additional thermal damage to uncharred wood in the load capacity calculations by including a zero-strength layer in the dimensions of the residual cross section (Figure 4).

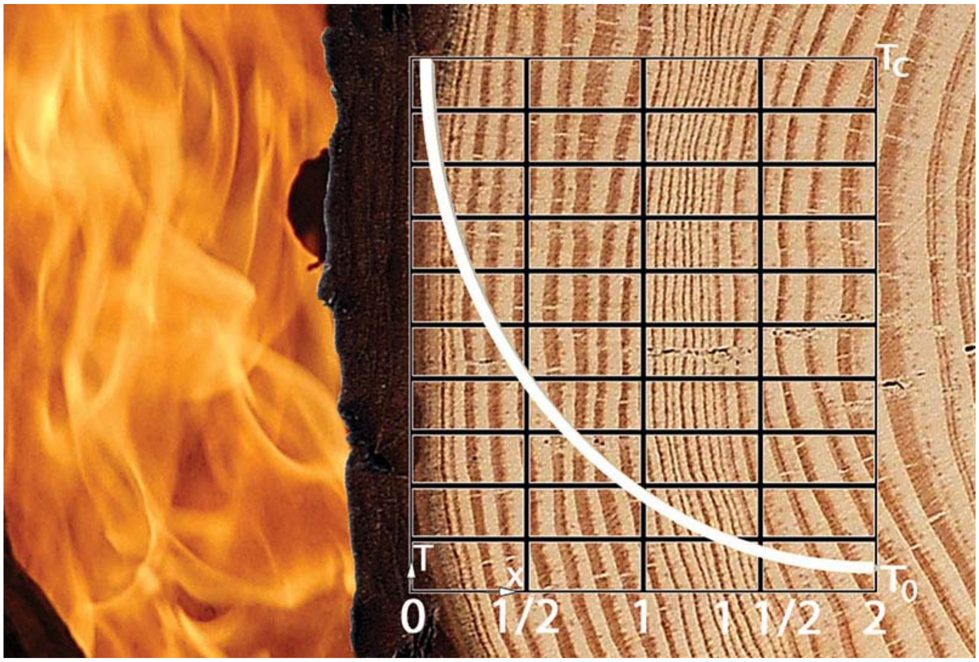

Figure 3. Illustration of Temperature Gradient in Fire-Exposed Wood

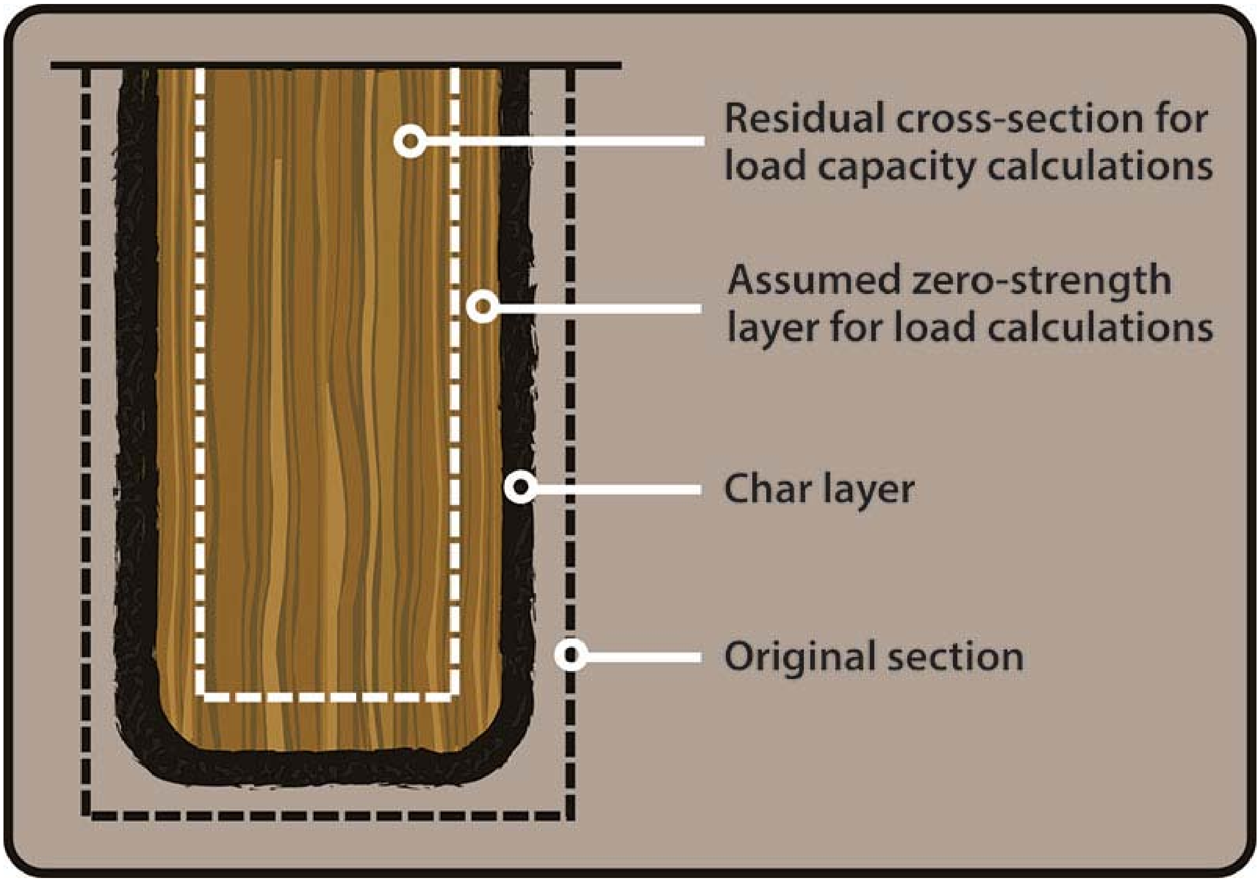

Figure 4. Illustration of Zero-Strength Layer Model of Fire-Damaged Wood Beam

In "Evaluation, Maintenance and Upgrading of Wood Structures, A Guide and Commentary" published by the American Society of Civil Engineers in 1982, recommendations for evaluation of fire damage were for "removal" of a fixed amount of wood. Recommendations included removal of the char layer plus approximately ¼ inch or less of wood below the base of the char layer. For members controlled by compressive strength or stiffness, the recommendation was that no additional adjustment beyond removal of ¼ inch was necessary to apply the basic allowable design stresses to the residual cross-sectional area. For members controlled by bending strength or stiffness, the recommendation was either removal of an additional 0.625 inch or removal of an additional ¼ inch in combination with a 10% reduction in the allowable design value used to calculate the load capacity of the residual cross-sectional area.

The code accepted methodology for calculating fire resistance ratings for heavy timber members addresses the anticipated thermal degrade effect on load capacity in the fire test by assuming an additional equivalent thickness having no strength and stiffness and by using "room temperature" published properties for the residual cross sectional area. The analysis assumption is that "damaged" wood provides an "equivalent" thickness of load capacity. In the fire resistance calculation methodology in the NDS (Chapter 16), the equivalent thickness for the heated and thus potentially damaged section is 20% of the calculated char depth. Using the normal assumption of a char rate of 1.5 inches per hour, the 20% calculation for the zero-strength layer is equal to 0.3 inch for a one-hour fire resistance rating. This 1.2 factor adjusts the thickness to reflect the fire duration and its likely impact on thermal penetration into the wood interior. The methodology has been shown to be applicable to both dimension lumber members as well as heavy timber members.

It is likely that a post-fire temperature profile will be flatter and of longer duration than the standard fire resistance test profile. Longer duration of elevated temperature in the interior portion of the member may increase the permanent loss in strength. The total duration includes both the fire and the post-fire period of elevated internal temperatures. The temperature at the char layer base should quickly be considerably less once the fire is extinguished and thus reduce the thickness of wood subjected to the more severe elevated temperatures.

In applying the methodology to the available strength data for permanent strength loss and the temperature profile reported for ASTM E119 fire exposure for various durations, the authors concluded that 0.1 inch to 0.3 inch is a reasonable recommendation for the zero-strength layer of a member loaded in compression in a post-fire load capacity analysis when used with the NDS adjusted design values. For members loaded in tension or bending, the recommendations are a thickness of 0.3 inch to 0.5 inch. These recommendations assume that the zero-strength layer is not physically removed from the member and the temperature at the center of the timber did not increase based on the likely temperature profile during the fire. One can further adjust the depth of the zero-strength layer downward by a fraction (e.g. 50%) of any uncharred depth removed for appearance reasons. Selection of values between 0.3 inch and 0.5 inch should be based on the duration of the fire as reflected in the observed char depth and location of members relative to direct exposure to flames. The observed thickness of the residual char layer will be less than the observed reduction in the dimensions of the charred member due to shrinkage of the char layer. In the context of these recommendations, 0.3 inch for compressive members and 0.5 inch for tension and bending members are the more conservative values for the thickness of the zero-strength layer in the calculation of load capacity.

In continuation of the example,

The RDP obtains measurements of the char free cross section. In this example, measurements indicated the residual width B' of the beam was 10.6 inches and residual height D' was 14.6 inches .

Available information on the fire indicated the beam was directly exposed to flames and that the fire was extinguished shortly after flashover. The intense short-duration fire produced about ½ inch char but thermal penetration into uncharred wood was likely limited. Thus, the conclusion in this example is that the additional reduction via a zero-strength layer of 0.3 inch is appropriate for calculation of residual load capacity.

To estimate the effective post-fire B and D dimensions.

B* = effective post-fire width= B' – 2(0.3) = 10.6 in. - 2(0.3) = 10.0 in.

D*= effective post-fire depth= D' – (0.3) = 14.6 in. – 0.3 = 14.3 in.

With Step 2 completed, the RDP has the basic information (B* and D* estimates) needed to conduct a preliminary structural analysis with respect to adequacy of the example fire-exposed timber floor beams. This preliminary structural analysis is conducted using the NDS adjusted design values for the grade/species as installed (if known) or new No. 2 Southern Pine timber. If the results are favorable with respect to demonstrating code compliance, a decision can be made by the RDP and client to further process the timbers to reduce them to their final dimensions and establish the grade and species of the beam whereby the structural design properties of the processed timbers will be available for use by the RDP.

Step 3. Documenting the Species, Grade, and Size of Each Timber

In this step, add the potential impact that the reduced cross section had on the structural grade of the timbers.

This step is necessary because visual stress grading rules are based on member size and characteristics (such as knots) of the outer zones of a member that greatly impact stress grade results.

With the timbers "clean" and reduced to their final dimensions, the RDP should contact a supervisory grading agency to evaluate all of the affected timbers in the structure. A list of grading agencies is available on the web site of the American Lumber Standard Committee, Inc (alsc.org). The grading agency can make a qualified statement for each timber based on what grade characteristics are evident for each beam. For example, by viewing a beam in-situ, the grading agency can conclude that the highest possible grade for the specific beam is No. 2 because the beam exhibits characteristics that exclude it from the No. 1 grade (alsc.org). Knowing the most optimistic grade for each beam, the RDP would be required to make the necessary judgments on a reasonable "design" value to use in the engineering process. The maximum potential grade for each beam should be established and documented by the engaged supervisory grading agency. Also, the RDP should measure and record the residual size of each timber for use when checking all fire-exposed timbers in the structure. The final sizes may be different from the sizes calculated under Step 2.

With Step 3 completed (the timber species or species group identified, visual stress rated grades confirmed, and section dimensions recorded for each timber), the RDP has an available set of visual stress rated design values for each timber to use with the effective post-fire section B* and D* dimensions. The RDP should also verify that the timbers are "sound" and have not been damaged by factors other than fire exposure.

Additional Considerations

Since the timbers have been in-service, they may be decayed and thus timbers should be thoroughly inspected for presence of decay.

Decay in a structural timber trumps all other factors that impact strength and stiffness, and therefore, a decayed timber cannot be relied upon to support in-service loads.

The load history of the timbers may be important. The possibility of overloads in-service, or cumulative damage, should be investigated.

The authors limited the scope of this article to solid sawn timbers. Laminations of different grades are often used in construction of a glued laminated timber. The inability to view the wide faces of the interior laminations will complicate the necessary re-grading of the residual beam. In addition, glued laminated timbers use very high quality outer tension laminations and the loss of these tension laminations due to a fire can severely impact the possibility of salvaging these timbers.

Conclusion

Structural evaluation of an existing wood structure, even without fire exposure, is an order of magnitude more difficult than the design of a new structure with new materials. In addition to collecting basic input information for structural analyses (species, timber sections, timber grades, timber condition, etc.), structural design experience is valuable as engineering judgment is likely to be needed in each specific case.

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Fire Protection Ability of Wood Coverings

Birgit A-L Östman

Abstract

The low thermal conductivity and slow charring rate of wood products may protect underlying products from being heated and ignited. A literature survey shows that such fire protective behavior of wood coverings has been verified by different methodologies in several countries in and outside Europe. A new European system with K classes for the fire protection ability of coverings has been utilized for wood products. The classes are based on full-scale furnace testing, and the main parameter is the temperature behind the fire-exposed panel after different time intervals. Three levels are defined: 10, 30 and 60 min. An extensive test program has been performed according to the new European system. The results demonstrate that all K classes may be achieved for wood-based panels (particle board, plywood, solid wood panels, OSB - Oriented Strand Board and hardboard), and for solid wood panelling and cladding. The criteria for wood products are based mainly on panel thickness. The thickness for achieving each K class may vary slightly, depending on the wood product type and on mounting conditions and fixing means. Typical thickness to reach 10 min fire protection is 10-15 mm, for 30 min 24 -30 mm, and for 60 min protection 52-54 mm. The end-use applications of wood products with K classes are mainly as wall and ceiling coverings and for protection of underlying materials and structures. Examples are protection of timber structures from becoming charred, and protection of steel structures from reaching high temperatures. K classification is required by building regulations in some countries, e. g. Germany, Denmark and Sweden.

KEYWORDS : *Fire Protection, Heat Insulation, Wood Products, Structural Design, Temperature Rise*

Introduction

The low thermal conductivity and slow charring rate of wood products may protect underlying materials from being heated and ignited. A literature survey shows that such fire protective behavior of wood coverings has been verified by different methodologies in several countries in and outside Europe. These studies have often been performed to demonstrate the use of component additive methods to calculate the separational fire resistance of wood assemblies and to provide input data (Norén and Östman 1985, König et al. 2000) to be used for modelling, e. g. in the fire part of Eurocode 5 (EN 1995-1-2), the structural design code for Europe. Eurocode 5 uses the term ‘basic insulation value’ which is closely related to the fire protection ability.

A European system with K classes for the fire protection ability of building panels has been introduced and is defined in (EN 13501-2). The K classes are based on full-scale furnace testing in horizontal orientation according to (EN 14135), and the main parameter is the temperature behind the panel after different time intervals (10, 30 and 60 min). No collapse or falling parts are allowed. The test principle is illustrated in Figure 1.

The aim of the K classes is to provide fire protection of underlying parts of a structure, e.g. the insulation in a wall or floor element. Two types of K classes are defined, depending on the substrate behind. Class K1 10 includes substrates with density less than 300 kg/m3, while Classes K2 10 - K2 60 include all substrates, so in practice it is sufficient to verify K2 classes. Class K1 10 is used and required only in Denmark.

The K classes originate from the Nordic countries, where they have been used mainly for gypsum plasterboards, since the Nordic criteria also include reaction-to-fire requirements. However, in the European system, only fire

Figure 1. Principle for Testing Fire Protection Ability According to EN 14135.

A summary of the test results and literature data has been published (Östman and Boström 2014). Full data are presented in (Östman et al. 2014). Partial results are included in technical guidelines (Östman et al. 2014).

Fire Testing and Classification

An extensive test program on verifying K class for different wood products has been performed using exactly the European standard methodology required. The wood products have been tested in a horizontal furnace according to the European test method Coverings - Determination of fire protection ability (EN 14135).

Different thicknesses of covering, design and geometry for joints and fixing methods of the products are included. In each test, two full size specimens 3,0 x 2,4 m were included. A series of pretesting with smaller elements 1,0 x 2,4 m was also performed.

resistance criteria prevail, so this is a great opportunity for wood products to demonstrate their fire protection abilities.

Most of the previous work has been performed in model-scale furnaces of different sizes with either a wood substrate, a mineral insulation product or a cavity behind. The case with mineral insulation behind is generally considered to be the worst case. Only some of the US data (White 1982 a and b, White 2003) include foam plastic insulations as substrate. The criteria for temperature increase behind the panel have usually been either 140 or 250 K, but this has been neglected in the present analysis, since the temperature increase is quite rapid at these temperatures and results in only about one minute difference or less.

It is obvious from the literature review that panel thickness is the most important factor for the contribution to fire resistance for both wood-based panels and gypsum plasterboards. Density has generally a minor effect at mean densities about 500-700 kg/m3, which include most wood products.

Similar thickness of the wood products to reach 10 and 30 min fire protection has been demonstrated. These data are promising for reaching European K class, but the methodologies used have been different, so further testing according to the European standards is needed to reach the European K classes.

Mounting and Fixing

All products were mounted on the substrate prescribed in EN 14135, 19 mm chipboard 680 kg/m3, without any air gap or cavity behind.

The coverings were fixed to the substrate in the same way as in practice, i.e. with screws for all wood-based panels except hardboards/medium board, where brads were used, and with nails for solid wood panelling and cladding.

All elements consisted of segments of the tested covering with joints according to EN 14135. The supporting system consisted of a framework of wooden beams with cc 600 mm and the chipboard substrate was mounted on the lower side of the framework.

Further details on the mounting and fixing are given in (Östman et al. 2014, Hilling and Boström 2009, Hilling et al. 2009).

Typical design of test elements and instrumentation of full size specimen is shown in Figure 2.

Furnace control

The furnace was controlled in accordance with EN 1363-1 to follow the standard time / temperature curve. The furnace temperature was measured with five plate thermometers and the measuring junctions were positioned approximately 100 mm below the fire-exposed

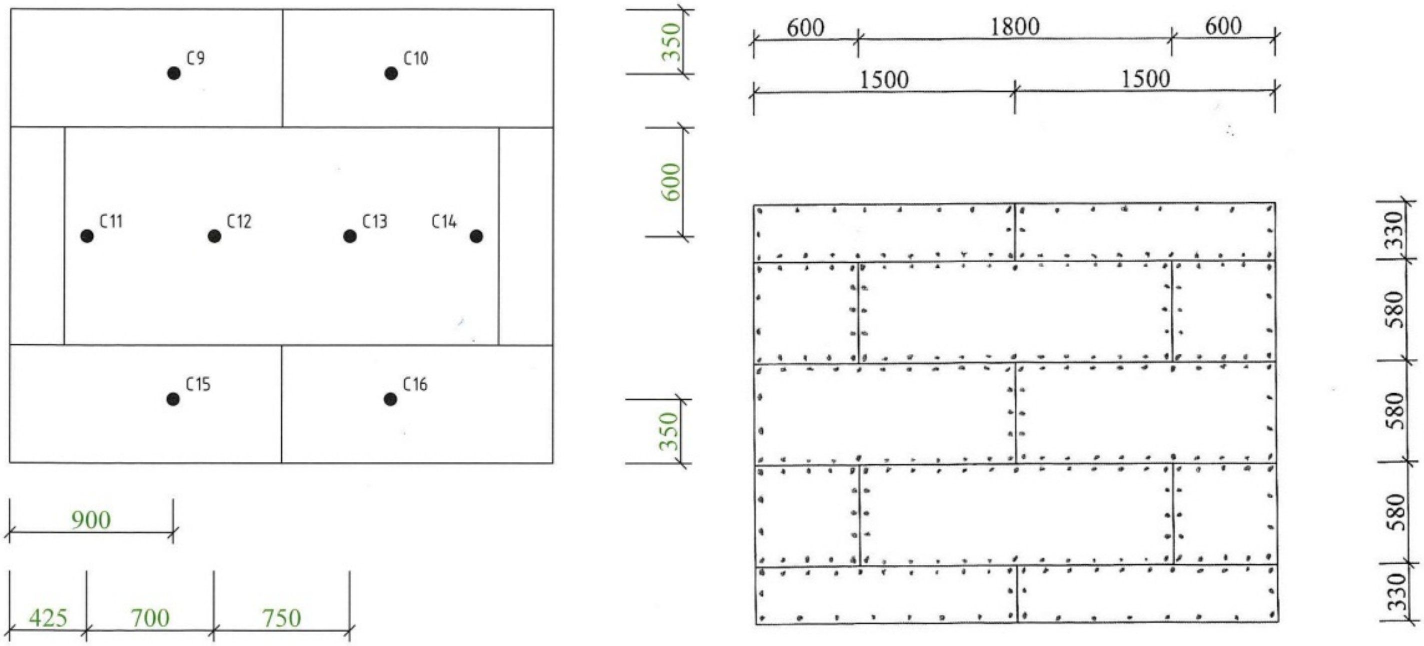


Figure 2. Typical Design of Segments in a Full Size Tested Covering 3.0 x 2.4 m with Joints According to EN 14135. Thermocouples between the tested covering and the substrate are shown on the left, and typical screw spacing on the right (screw size and edge distance not to scale) (Hilling et al. 2012).

surface at the commencement of the test. The average temperature and the temperature of each plate thermometer were recorded and reported in the test reports.

The pressure in the furnace in relation to the ambient pressure in the test hall was measured and controlled 100 mm below the fire-exposed surface of the test specimen. The furnace was controlled to an overpressure of approximately 20 Pa.

Measurements and Observations

The temperature rise on the lower side of the chipboard substrate was measured with 8-9 thermocouples for the full size elements and recorded. Photographs were taken before and after the test.

After the test, the tested covering was inspected for collapse and the chipboard substrate for charring.

Fire Classification Criteria

A covering designated K2 as defined in EN 13501-2 is considered to give the prescribed protection for materials behind the covering if, during a test in accordance with EN 14135, there is no collapse of the covering or parts of it within the classification period (10 min, 30 min or 60 min), and also if the following requirements are fulfilled.

For a covering without a cavity or cavities behind it:

- the mean temperature measured on the lower side of the substrate shall not exceed the initial temperature by more than 250 K
- the maximum temperature measured at any point of this side shall not exceed the initial temperature by more than 270 K, and
- after the test, there shall be no burnt, charred, melted or shrunk material at any point of the substrate.

For a covering with a cavity or cavities behind it:

- the mean temperature measured on the lower side of the substrate and the mean temperature measured on the unexposed side of the covering shall not exceed the initial temperature by more than 250 K
- the maximum temperature measured at any point of these sides shall not exceed the initial temperature by more than 270 K, and
- after the test, there shall be no burnt, charred, melted or shrunk material at any point of the substrate and at any point of the unexposed side of the covering.

Table 1. Wood Products Tested

Wood Product	EN Harmonized Product Standard	Thickness, mm	Mean Density, kg/m^3	Fixing Device (nail, screw, etc.)	Joints
Particleboard	EN 13986	10, 12, 22, 25	580-680	Screw	Square Edges, Tongue and Groove (T&G)
Plywood	EN 13986	9, 12, 24	470-530	Screw	Square Edges, T&G
Hardboard	EN 13986	9	770	Brad	Square Edges
OSB	EN 13986	10, 12, 25, 30	590-600	Screw	Square Edges, T&G
SWP	EN 13986	13, 26, 52	440-490	Screw	Square Edges, T&G
SWPC	EN 14915	15, 27	450-460	Nail	T&G

Wood Products Tested

Different types of wood products according to the European harmonized standards EN 13986 and EN 14915 have been tested, five types of wood-based panels (particle board, plywood, oriented strand board (OSB), hardboard/medium board and multilayer solid wood panels (SWP)) and solid wood paneling and cladding (SWPC), see Table 1.

Joints and fixing devices

The joints within a wood element were either with square edges or with tongue and groove profiles without gaps. Typical design is given in Figure 3. The thickness at the joints was the same as for the wood product.

The fixing devices were chosen according to industry guidance and producers´ recommendations, see Table 2. The edge distance was 3d (nominal diameter) for wood-based panels and 5d for SWPC. All dimensions of the fixing devices used are included for completeness.

Table 2. Fixing Devices Used for Wood Products

Fixing Device	Length/ Diameter (d), mm	Spacing at Edge, mm	Used For:
Screw	25/2.5, 30/3.5, 30/3.9, 30/4.2, 41/4.2, 50/3.5, 57/4.2, 75/4.1	200	Particleboard, OSB, Plywood, SWP
Brad	40/1.7	100	Hardboard
Nail	50/2.0, 50/3.0, 60/2.3	600	SWPC

Fire test results and analysis

Typical examples of pictures from the EN 14135 fire tests are shown in Figure 4 and 5.

The pretest results with smaller 1,0 x 2,4 m specimens for 10 and 30 minutes exposure time (Hilling and Boström) showed that all temperatures were below the maximum temperature rise, so standard testing with full-size elements started.

The fire test results for the full size elements at all fire exposure times (Hilling et al. 2009) have been analyzed in terms of panel thickness, type of wood product, joints and char at substrate. The results are shown in Figures 6 and 7.

Most tested products with no char at substrate also passed the temperature rise criterion of < 250 K at substrate. But some of the products passing the temperature criterion had some char at the substrate behind the covering. The charring was caused by heat

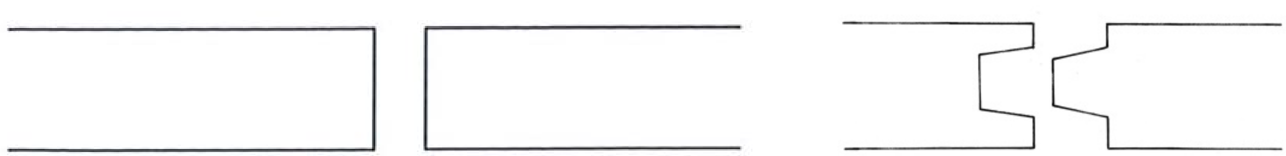


Figure 3. Typical Design of Joints with Square Edges (left) or with Tongue and Groove (right).

(a) **(b)** **(c)**

Figure 4. Testing Solid Wood Panelling. (a) The Exposed Side of the Wood Covering Before, and (b) After Fire Testing. (c) The Substrate Behind the Covering After the Fire Testing.

exposure at joints or fixing devices. However, no difference between butt (square) and t&g joints could be observed, see lower diagram in Figure 7.

The conclusion is that the EN 13501-2 requirements for both maximum temperature rise on the substrate and lack of charring are useful as test criteria.

The fire protection ability of wood products with different thicknesses is illustrated in Figure 7. The dependence on panel thickness is clear. The real protection time is longer, but not recorded, since the tests had to be terminated at the exact end times according to EN 14135 in order to be able to observe possible charring at the substrate.

The pretesting and the full size data are quite similar, especially at 10 min fire exposure, for which most of the tests were performed (Östman and Boström 2014).

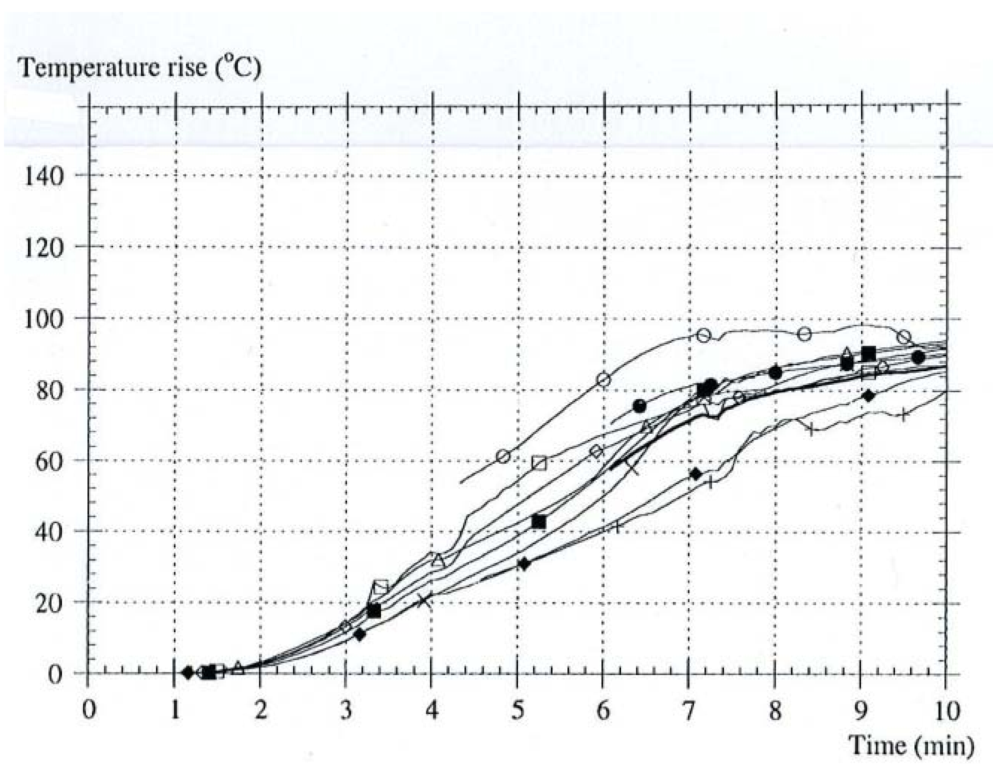
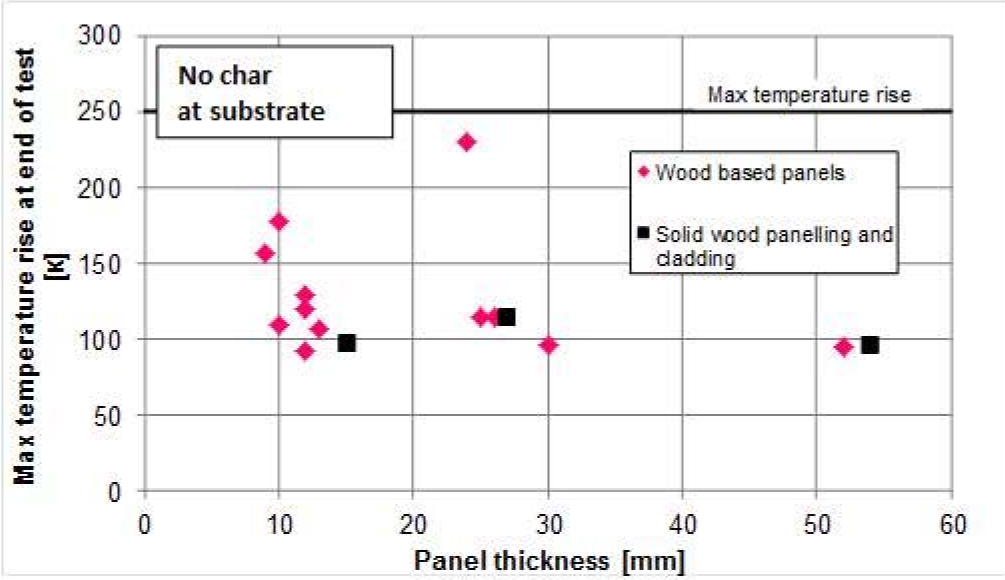


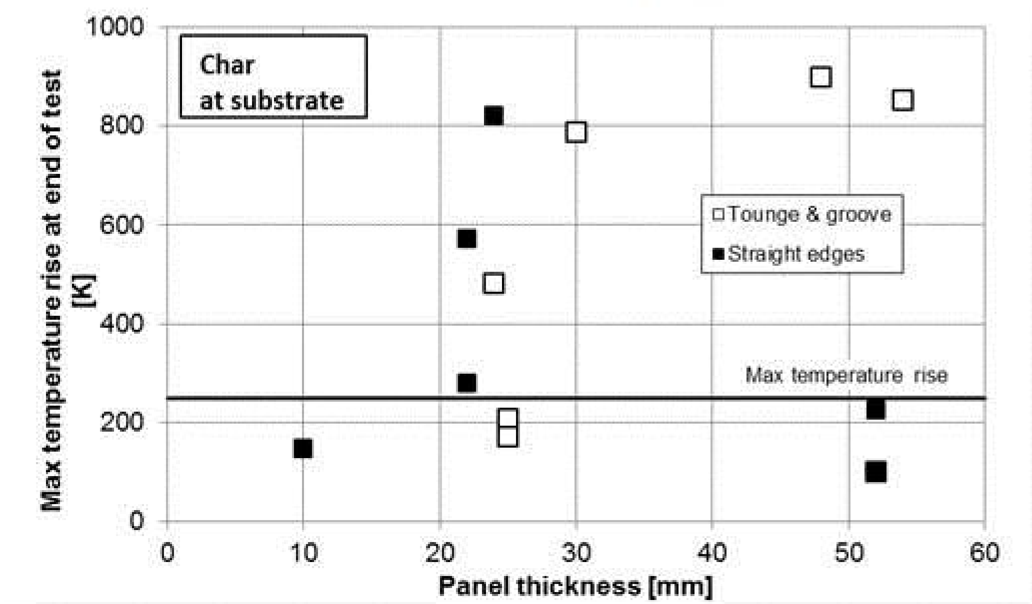
Figure 5. Example of Measured Temperature Behind the Tested Solid Wood Panelling.

Figure 6. Full-Scale Test Results as Maximum Temperature Rise at the Substrate Behind the Tested Covering at Exposure Times 10, 30 and 60 Min.

Above: For Wood Products with No Char at the Substrate Behind the Covering.



Below: For Wood Products with Char at Substrate. All Charring Appeared at the Joints or Fixing Devices.



K classes for wood products

The classification of the fire protection ability of the wood products tested has been performed according to the CWFT - Classification Without Further Testing procedure (CONSTRUCT 2004). This procedure may be used for products which have been proven to be stable in a given European class. CWFT is a list of generic products, not a list of proprietary products. Products claiming CWFT must be clearly above the lower class limits, to provide a safety margin.

Wood products are good examples of products having a stable fire performance. The CWFT approach has earlier been applied for the reaction to fire performance of several wood products. Results have been published e.g. (Östman and Mikkola 2006). The request for K classes is the first CWFT case dealing with fire resistance performance.

Detailed documentation has been supplied to the European Commission services. The documentation was carefully checked in several steps and at different levels and finally approved by SCC, the European Standing Committee on Construction. The final classification is published in the Official Journal of the European Commission (COMMISSION DELEGATED REGULATION 2014).

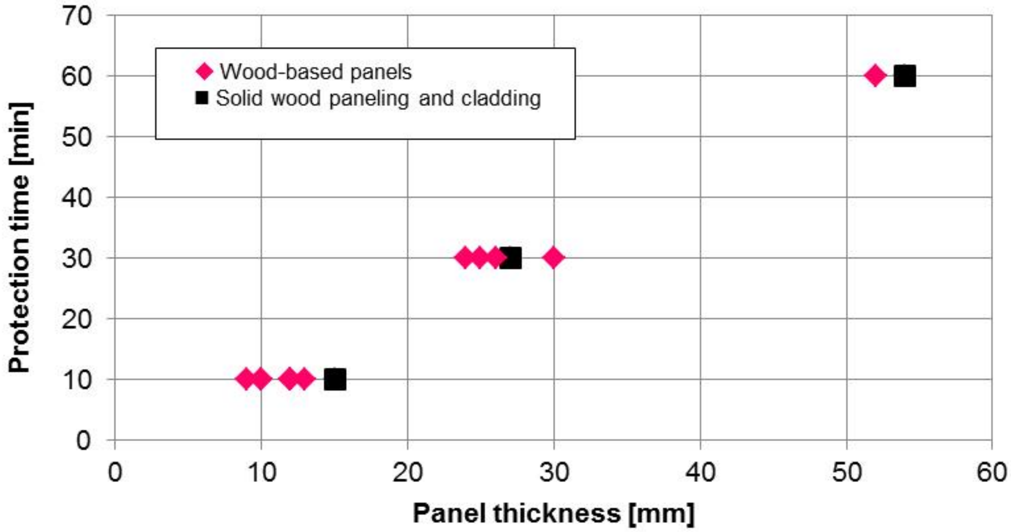
In all cases, the criteria according to EN 13501-2 were fulfilled:

The maximum temperature rise behind the covering was less than 250 K

There was no char on the substrate behind the covering

The safety margin to the class limit is generally very large and in average > 100 K.

Figure 7. The Fire Protection Ability (Time) According to EN 14135 for Wood-Based Panels and Solid Wood Panelling with Different Thicknesses Tested at 10, 30 and 60 Minutes (Hilling et al. 2012).



Conclusions and Applications

The main product parameter influencing the fire protection ability of wood-based panels and solid wood panelling and cladding is thickness, while density has a minor influence for the density ranges studied.

Wood-based panels, i.e. particle board, plywood, OSB and solid wood panels (according to EN 13986) at least 10 mm thick, and hardboard/medium board at least 9 mm thick fulfil Classes K1 10 (for substrates ≥ 300 kg/m3) and K2 10. Wood-based panels and solid wood panels at least 24-30 mm thick fulfil Class K2 30. Solid wood panels at least 52 mm thick fulfil Class K2 60.

Solid wood panelling and cladding (according to EN 14915) planed with tongue and groove joints and with equal thicknesses of at least 15 mm fulfil Classes K1 10 (for substrates ≥ 300 kg/m3) and K2 10. Solid wood panelling and cladding at least 27 mm thick fulfil Class K2 30, and of at least 2 x 27 mm thick fulfil Class K2 60.

Wood-based products fulfilling the different K classes are summarised in Table 4 (COMMISSION DELEGATED REGULATION 2014).

The end-use applications of K-classified wood products are mainly wall and ceiling coverings and for protection of underlying materials. Examples are protection of timber structures from being charred, and protection of steel structures from reaching high temperatures. K classes are required by building regulations in some countries, e.g. Germany, Denmark and Sweden.

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Recent Advances in Fire Performance of Cross-Laminated Timber

Christian Dagenais, Lindsay Osborne

Abstract

Various aspects of the fire performance of cross-laminated timber (CLT) have been evaluated to help support its use in construction projects. The 2013 U.S. Edition of the CLT Handbook contains a comprehensive account of this work and provides design methodologies. Additional recent investigations have since been carried out to further enhance this knowledge. A summary of some of the most up-to-date CLT fire research is presented; which includes fire resistance of CLT assemblies and a CLT timber-concrete composite floor, flame spread ratings, fire stopping considerations and real-scale fire tests.

Introduction

Wood construction is experiencing a renaissance in that wood products for use in construction are undergoing a rebirth of sorts. Not only are traditional wood products being used in different ways, but a host of innovative new engineered wood products and building systems, including structural composite lumber and mass timber frames and plates, are bursting into the marketplace. The advent of these products and systems, which can have impressive strength, durability and fire performance, are supporting initiatives to potentially allow taller and larger wood construction. Five- and six-storey mid-rise wood construction is already prominent in some parts of the U.S., particularly on the West Coast. There are several international tall wood building projects, either completed or under construction; some reach as high as fourteen stories. Currently, in Canada, the Wood Innovation Design Centre (WIDC) is the tallest modern wood structure in North America and there are three other projects that are presently in the design stage.

KEYWORDS : *Fire Resistance, Cross-Laminated Timber, Wood Products, Fire Stopping*

One product that may prove to be instrumental for realizing these larger wood projects is cross-laminated timber (CLT). CLT is similar to glue-laminated timber except that it uses alternating perpendicular glued layers and is formed into thick slabs, which can make up walls or floors. CLT is particularly advantageous because most of it can be prefabricated off-site which in-turn can significantly reduce construction time and, ultimately, the total building cost. FPInnovations has developed a handbook which details many design considerations for CLT (Karacabeyli and Douglas 2013), of which Dr. Robert White was a major contributor to the "Fire" chapter (Dagenais et al. 2013). This Fire chapter discusses fire resistance of CLT, connections, interior finish considerations, and how to detail service penetrations. Since its publication in 2013, more research has been done to further the understanding of the performance of CLT in fire. Moreover, CLT is now a recognized building system for use in Type VI construction in the 2015 International Building Code (IBC). The following is an account of some of the most up

Figure 1 – Unexposed Side of Wall Assembly at 2 Hours into Test

Table 1 – Fire resistance test results (Dagenais 2014)

	# Plies	ANSI/APA PRG 320 Stress Grade	Thickness (in)	Gypsum Board Protection	Superimposed Load	Failure Time	Type of Failure
WALL	3	E2	4 1/2	2 x 1/2" Type X	22,818 lb/ft	1 h 46 min	R
	5	E1	6 7/8	Unprotected	22,818 lb/ft	1 h 53 min	E
	5	V2	4 1/8	Unprotected	4,934 lb/ft	57 min	R
	3 [1]	E1	4 1/8	Unprotected	20,214 lb/ft	32 min	R
	5 [2]	E1	6 7/8	1x 5/8" Type X (both sides)	8,702 lb/ft	3 h 06 min	R
	5 [3]	E1	6 7/8	2 x 5/8"	30,767 lb/ft	3 hr 39 min	R
FLOOR	3	E2	4 1/2	2 x 1/2" Type X	56 psf	1 h 17 min	[4]
	5	E1	6 7/8	Unprotected	246 psf	1 h 36 min	E
	3	V2	4 1/8	1 x 5/8" Type X	50 psf	1 h 26 min	R
	5	V2	6 7/8	1 x 5/8" Type X	169 psf	2 h 04 min	E
	7	V2	9 3/8	Unprotected	305 psf	2 h 58 min	R
	5 [3]	E1	6 7/8	3 1/2" Glass Fiber Insulation 5/8" Resilient Channels 1 x 5/8" Type X	196 psf	2 h 08 min	R

*R—Structural Failure, E—Integrity Failure

[1] in Collaboration with CWC, [2] In Collaboration with AWC, [3] (Osborne 2014), [4] Test Was Stopped Prematurely Due to Equipment Safety Concerns

-to-date CLT fire research conducted by FPInnovations or in collaboration with, among others, the National Research Council Canada (NRCC).

Fire Resistance Testing

Fire resistance testing has been conducted in conformance with ASTM E 119 and CAN/ULC-S101 standards for assemblies that were fully unprotected, protected with gypsum board, or protected with a combination of gypsum board and insulation. The CLT panels were manufactured with lumber and structural adhesive conforming to ANSI/APA PRG-320. Table 1 summarizes the fire resistance test results. Figure 1 depicts the unexposed face of a wall 2 hours into a standard test which is still at ambient temperature and safe to touch.

Figure 2. CLT-Concrete Composite Floor Under Construction

The first test series data was used to develop a fire resistance calculation methodology, which has now been incorporated into Chapter 16 of the 2015 National Design Specification for Wood Construction (NDS), and is therefore a recognized method in the 2015 IBC. The actual failure times of assemblies correlate well to those predicted with the method, while being conservative for fire exposure beyond 3 hours.

Timber-Concrete Composite Floors

A timber-concrete composite (TCC) floor using CLT (Figure 2), consisting of a 6⅞" (5-ply) CLT and 3½" concrete was evaluated for fire resistance to observe the interaction between the two materials when exposed to the standard time-temperature fire curve (Osborne 2015). Self-tapping wood screws at 45º were used as shear connectors. This type of system has the advantage of being able to reach longer spans as well as having

Figure 3. TCC Floor Assembly Using CLT After the Test

enhanced acoustic and serviceability performance. A superimposed load of 50 psf was applied throughout the test, representing the live load specified for offices and a greater load than that required for residential occupancies. The floor deflected until structural failure was reached at 3 h 34 m. The assembly being lifted off the furnace is shown in Figure 3.

Temperatures at the interface between the CLT and concrete increased by 68ºF and at the shear connector (also at the interface) by 200ºF, however mid-depth into the concrete temperature rise was minimal, indicating that negligible heat was being transferred into the concrete itself. An average effective charring rate in the CLT of 1.6 in/hr was measured from embedded thermocouple data, which accounts for heat delamination of plies due to adhesive failure. This behavior was also observed in other CLT fire resistance tests and led to the development of a 'stepped' charring model in the U.S. CLT Handbook fire chapter.

Figure 4. Flame Spread Index Testing of CLT in Steiner Tunnel

Flame Spread Index

A 4⅛" 3-ply CLT panel of the E1 stress grade was evaluated for surface burning characteristics following the ASTM E84 test method. The CLT panel exhibited a low flame spread index of 35, thus easily meeting Class B requirements (AWC 2013).

Furthermore, two 4⅛" (3-ply) CLT panels, of E1 and V2 stress grades, were evaluated for flame spread rating following CAN/ULC-S102 (Dagenais 2014). This standard is similar to ASTM E84 but there are differences which do not allow for the results to be directly comparable. Nevertheless, the CLT panels achieved ratings of 35 and 40, respectively. A similar 3-ply E1 stress grade panel was also evaluated with the addition of a surface applied intumescent coating, which reduced the FSR to 25, and would be expected to fall under Class A if tested per ASTM E84 (Dagenais 2013). Figure 4 displays a CLT panel being tested for flame spread.

Fire Stopping

Firestop systems are intended to ensure the integrity of a fire-resistance rated compartment by maintaining the fire-resistance rating of the floor and/or wall assemblies at construction joints and where elements pass through them (penetrations). Testing, in accordance with CAN/ULC S115 (similar to ASTM E 814) has evaluated a few commercially available fire-rated joint fillers and sealing tapes already approved for use with concrete for construction joints and full penetrations (Dagenais 2014).

Testing showed that these types of products are capable of achieving 1 ½ h and 2 h fire resistance with CLT, but two important points should be considered to prolong the effectiveness of the firestop system. Firstly, joint firestops should be installed at a location that will be least impacted by potential charring of the assembly (such as closer to the unexposed surface, as shown in Figure 5). Secondly, through penetrations (and their firestops) should be installed to limit ignition or charring of the wood. That is to say, elements that could transfer heat to the CLT should not directly touch the CLT; they should pass through the centre of an opening and be properly insulated over their perimeter. Figure 6 depicts an example of a suitable configuration for a penetration firestop.

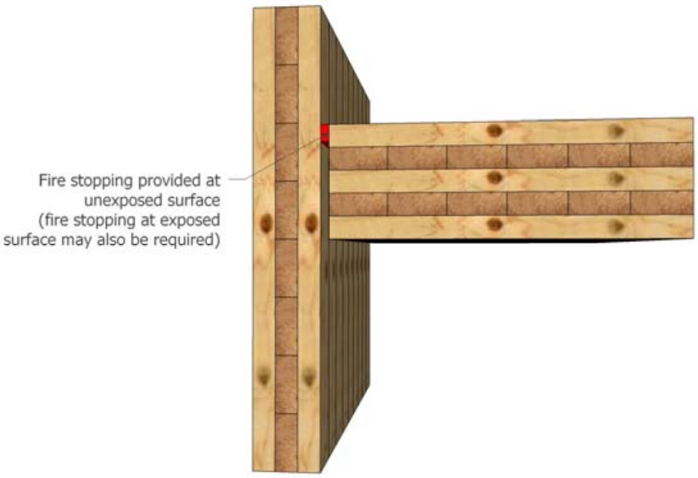

Figure 5. Joint Firestop at Unexposed Surface

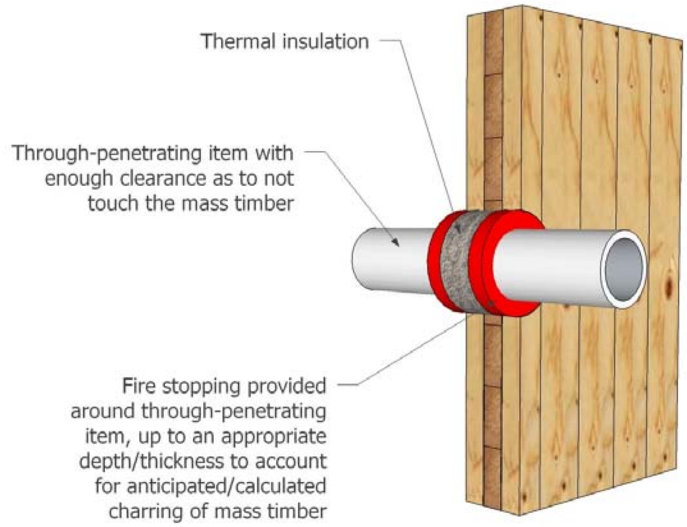

Figure 6. Firestopping of Through Penetration

Real-Scale Testing of CLT Fire Performance

The fire tests described above are, among others, typically the primary ones used to assess a building element or assembly for Code compliance, which are evaluated as components. Given that CLT is a relatively new product in North America, a series of real-scale fire tests have been conducted to evaluate the fire performance of CLT as a complete building system.

A research consortium comprised of the NRCC, the Canadian Wood Council and FPInnovations evaluated the encapsulation and potential contribution to fire of a 3-storey mock-up apartment (Taber et al. 2014). The test arrangement was 28’ long by 21’6” wide, replicating a one-bedroom unit on the first floor of a mid-rise building. CLT panels protected with 2 layers of ½” Type X gypsum board were used. The fuel load within the fire floor comprised of typical furniture and contents found in residential occupancies. The apartment involved in fire is shown in Figure 7. After 40 min into the test, the fuel load was entirely consumed. The test was terminated after 3 hours. The test showed that properly encapsulated CLT structures can withstand complete burnout based on a residential fuel load. It also demonstrated the effectiveness of encapsulation in delaying the time to ignition of wood components and their potential contribution to fire growth.

Figure 7. Mid-Rise CLT Apartment Test at CRC

A full-scale CLT shaft demonstration fire was completed to show how a mass timber shaft, for an elevator or exit stair, could withstand the effects of a severe fire in an adjacent apartment unit (Osborne and Dagenais 2015). The shaft measured 15’ x 8’2” x 29’ 6” high and the fire room, outfitted with a 95th percentile fuel load of 790 MJ/m^2, was 15’ x 17’ x 9’10” high. The entire structure used 6 ⅞” (5-ply) CLT, which was unprotected in the shaft. The fire room ceiling had 3 ½” of glass fibre insulation between steel ‘Z’ bars, ⅝” resilient channels, and 1 layer of ⅝” Type X gypsum board (and had previously demonstrated fire resistance of over 2 h, as listed in Table 1). The fire room walls had 2 layers of ⅝” Type X gypsum board (which achieved a 3 h fire resistance rating, as listed in Table 1); the shared wall between the shaft and the fire room had an additional wall built ¾” in front of the gypsum board for acoustic purposes; this wall used steel studs, 2 ½” rock fibre insulation, and one layer of ½” gypsum board. The fire was permitted to burn for 2 hours to reinforce that this structure, as a whole system, could meet and surpass 2 h fire resistance traditionally required for mid-rise and tall noncombustible construction. Figure 8 was taken during the initial fire growth. Throughout the test there was no smoke or heat penetration into the shaft whatsoever. Some gypsum board and rock fibre insulation was even still in place on

Figure 8. CLT Shaft Demonstration Fire

the walls after extinguishment. Once remaining debris was removed, it was evident that a significant portion of the CLT shaft wall remained uncharred, and any charring that did take place was less than ¼" deep.

Summary

Significant scientific efforts have been put into gaining a better understanding of the fire performance in CLT in North America. Fire resistance testing of CLT floor and wall assemblies has confirmed that this product can safely be used to achieve 2 h ratings, and beyond. Other aspects of fire performance, such as flame spread index and fire stopping methods, have also demonstrated assuring results. Real-scale experiments have established that CLT, when used as a complete building system, can provide equivalent or greater levels of fire safety compared to a building using non-combustible construction.

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