FIRE ENDURANCE MODEL FOR METAL-PLATE-CONNECTED WOOD TRUSSES

Robert H. White, USDA, Forest Service, Forest Products Laboratory, Madison, WI[1]
Steven M. Cramer, & Deepak K. Shrestha, Department of Civil and Environmental Engineering, University of Wisconsin–Madison, Madison, WI

INTRODUCTION

The primary objective of this work was to develop a model and user-friendly computer program that predicts single truss performance under combined structural load and fire conditions. This work included the experimental determination of the load-bearing capacity of 38- by 89-mm (nominal 2-by 4-in.) lumber and metal plate connections (MPC) under various fire exposures. The test results were used to obtain strength properties at elevated temperatures and to develop and validate thermal degrade models of the components. Such property data and degrade models are needed as input to the fire endurance truss model. The current model requires that the user specify the temperature development within the truss assembly. Future refinements of the model will expand its applicability to multiple-truss assemblies and include heat transfer analysis of protected truss assemblies.

The long-term aim of this project is to improve the market for lightweight engineered wood systems by understanding, improving, and gaining acceptance of their fire performance. By developing these fire endurance computer models and increasing flexibility in fire endurance design, we hope that the fire safety as well as the commercial-industrial markets for lightweight engineered wood systems will improve.

SAWTEF MODEL

The fire endurance truss model SAWTEF (Structural Analysis of Wood Trusses Exposed to Fire) predicts single truss performance for combined structural load and fire conditions. A pitched or parallel chord truss may be considered. The model considers nonlinearities introduced by nonlinear connection properties, fire degrade, and large displacements using established methods of structural and finite element analysis. [1]

The SAWTEF model has two main parts: a windows-oriented pre/post processor software for data input and output interpretation and structural analysis software. The model generates output for a single truss subject to assumed fire conditions, which includes for each time step and each member within the truss (1) displacements of the end of each member, (2) stress conditions within each member, and (3) percentage of remaining load capacity.

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The model requires the following input data:

1. truss geometry, including span, slope, individual member size and length, and truss plate size and orientation

2. wood member stiffness and strengths at room temperature, including tension, bending, and compression strength;

3. connector stiffness values at room temperature in tension;

4. vertical or lateral load magnitudes, or both; and

5. temperature magnitude and distributions within the truss for an assumed fire condition.

Loss of stiffness and strengths of wood members or connectors because of thermal degradation of wood are estimated within the program. As an alternative, the user may input this information if it is available.

COMPONENT TESTS

This project included a component testing program, which consisted of measuring the tension and bending behavior of lumber and truss plate connections under room temperature and fire conditions. This choice of emphasis of the testing program was based on the assumption that bottom chord members (subject to tension and bending forces) control truss fire endurance. But failure in the model is not limited to this assumption. Failure can also occur because of compassion of the top chord members or web members.

The experimental program involved tests on 38- by 89-mm (nominal 2- by 4-in.) Southern Pine lumber and 20-gauge metal connector plates. The 4.9-m-long specimens were loaded in tension in *a* specially made tension apparatus. In the middle of the tension apparatus, a 2.1- by 1.4-m furnace subjected 1.8 m of the specimen to high temperature or fire exposure.

Each loading condition was tested in two ways. In the constant temperature test, the specimens were heated in the furnace for 30 or 60 min at a constant temperature and then a ramp load was applied to failure. In the second test, the specimen was loaded to a constant tensile load and then exposed to fire exposure until failure. The four loading/fire exposure levels for the constant load tests consisted of two load levels (50 and 100 percent of design load), two fire exposures (ASTM E 119),[2] and an idealized plenum time-temperature curve. The idealized plenum time-temperature curve was 65,93, 188.260, and 327°C at 10, 20, 30, 45, and 60 min, respectively. The curve was derived from various ASTM E 119 tests of protected truss assemblies. The results were the time of failure and the time-elongation curve. We developed the thermal degrade models from the constant temperature tests and verified it with the constant load tests.

THEORETICAL MODELS

In this section, the theoretical models are briefly reviewed. They are fully discussed by Shrestha.[3] These models include the basic structural model, the heat transfer model incorporated within the program, the thermal degrade models that define the reduction in material properties with temperature, and the criteria that define the structural failure of the truss.

Structural Model

The structural model is based on established methods of structural and finite element analysis.[1] Connector elements consist of an assemblage of rigid links and springs to model the tooth-wood slip and eccentricities associated with these connectors. The truss is modeled as an assembly of wood elements and connector elements. The wood members are assumed to exhibit linear elastic behavior, while the MPC are assumed to have nonlinear elastic properties. The load-slip properties of the connection are specified by the three parameters (K, M_0, and M_1) of the equation developed by Foschi[4] for MPC. A large deformation-small rotation analysis was developed to accommodate the significant deformations witnessed in fire tests of assemblies.

Heat Transfer Model

The scope of this project was limited to developing a model that predicts the structural response when the temperature development within the assembly and within the members is given. Recent developments in modeling heat transfer within a wood member have included numerical models, such as finite difference and finite element, that include all factors involved in the thermal degradation of wood and changing boundary conditions. Incorporating such models within SAWTEF would not have been practical. In order to have a more self-contained program, a limited heat transfer model of the temperature profile of a wood element was built into the program. Based on some assumptions, an analytical model with a closed-form solution was developed. The surface temperature-time curves (STC) for the elements still need to be provided as input. The STC for the wood and metal plate elements are either obtained from an ASTM E 119 test report or a separate heat transfer analysis.

The model was developed from the conservation of energy differential equation. The heat generation term includes separate terms for the moisture effect and the pyrolysis effect. Moisture vaporization and wood pyrolysis are modeled with Arrhenius equations. By assuming that the wood member is suddenly subjected to a constant surface temperature on all four surfaces, a closed-form solution can be obtained. The temperature and the heat generation terms are represented by double Fourier series. Based on the component test data, correction factors were developed for the cases when the surface temperature was not constant.

The internal model provides a useful alternative when better data are not available. The program user has the option of inputting thermal degrade factors directly instead of the surface temperatures. Theoretical heat transfer models are available that can predict the temperature gradient in a protected wood member.

Thermal Degrade Models

The heat transfer model is used to predict the temperature at the center of the wood member. A parabolic temperature distribution within the member is then assumed with the specified surface temperature and the calculated center temperature. Using initial component test data, thermal degrade models were developed for the structural properties of the wood members and the MPC. The equation for the degradation of lumber properties is

$$\frac{P_t}{P_0} = \frac{T_0 t_e}{T_0 t_e + C_p A_t}$$

where

P_t is degraded property at given exposure time t_e (longitudinal modulus of elasticity (MOE), tensile strength, compressive strength, or bending strength of wood),

P_0 property corresponding to P_t measured at room temperature,

T_0 room temperature (°C),

t_e time or duration of exposure (min),

C_p correction factor ($T_c^{0.5}/100$) for MOE, $(T_c/198)^4$ for tensile and compressive strengths, and $(T_c/215)^6$ for bending strength, T_c center temperature (°C) at time t_e, and

A_t area under surface temperature-time curve defined by temperature 1/3 ($T_s + 2T_c$) minus the initial room temperature where T_s is surface temperature.

The correction factor is included to improve the fit of the data. Degrade data were not obtained for compression but were assumed to be the same as those for tension in the model. However, other research has indicated that degradation in compressive properties was not the same as for tensile properties. For the MPC, the Foschi's parameters are assumed to be linear functions of the exposed surface temperature with a break point at 200°C for the K parameter and 250°C for the M_0 and M_1 parameters.

When the thermal degradation of the components is known in greater detail, the thermal degrade factors can be inputted as a function of time. To develop more precise thermal degrade factors, the temperature profile within the assembly and its components needs to be known in greater detail. The default degrade factors for the wood components are based on a uniform temperature on four surfaces.

Failure Criteria

In this model, failure of a truss is assumed to occur when the load on a member exceeds its residual strength or the connection excessively slips. The model provides for a maximum combined stress index (CSI) for the wood members and a maximum plate failure index (PFI) for the MPC. The

CSI considers the combination of axial and bending stresses in the wood members based on the work of Zahn.[5] The index varies between 0 and 1, with 1 or greater indicating failure. The critical CSI value of 1 may be attained through a combination of bending and tensile stresses (typically occurring in the bottom chord of a truss) or a combination of bending and compressive stresses (typically occurring in the top chord of a truss).

The maximum PFI indicates the capacity consumed for a plate-wood contact area based upon the degrade of the original low-load stiffness of the connection. The index varies between 0 and 1, with 1 or greater indicating failure.

MODEL EVALUATION

Standard fire tests of five floor-ceiling truss assemblies were used to evaluate the model.[6–10] The assemblies were designed by the Tress Plate Institute (TPI), and the task of validating the fire rating of each assembly was assigned to independent agencies. All assemblies employed 38- by 89-mm (nominal 2- by 4-in.) Southern Pine lumber and 20-gauge metal connector plates. A typical representative truss from each floor-ceiling assembly was modeled.

By combining the given data with reasonable estimations of the missing data, each truss was analyzed with SAWTEF for design load and the reported plenum temperature exposure. The observed failure times for the five floor–ceiling assemblies are compared with the SAWTEF predictions for the representative truss of the respective assembly in Table 1. The predicted values were 16 percent lower on average than the observed failure times. The model generally under-predicted the actual failure time. This was reasonable since assembly performance was being compared to predicted single truss

Table 1. Observed failure times of floor–ceiling assemblies with predicted failure times for single representative trusses

Design number	Ceiling membrane	Reference	Failure time (min)	Predicted time (min)
FC–214	Double-layer 12.7-mm gypsum attached to bottom chords	8	76	76
FC–235	Single-layer 15.9-mm gypsum attached to bottom chords	6	50	38
FC–249	Single-layer 15.9-mm gypsum attached to furring channels	7	58	52
FC–426	Double-layer 15.9-mm gypsum attached to furring channels	9	112	86
R9500–1	Single-layer 15.9-mm gypsum attached to furring channels	10	60	45

performance. The representative truss did not incorporate the load-sharing effects of attached sheathing (both plywood and gypsum) and bracing members, which were present in the assemblies.

Several general observations were noted from the analyses of the five trusses. Deflection in the truss increased gradually through most of the test until a few minutes prior to failure. Deflections then increased exponentially approaching collapse. Because the model considers only the single truss, there was no load-sharing to provide even a momentary respite from impending collapse. The increase in deflections resulted from loss of stiffness caused by increasing temperature. As stiffness was lost, the capacity of the members was also increasingly consumed.

OTHER RESEARCH

This report covers the development of the fire endurance model. The development of improved fire resistant truss assemblies is being studied. Work is funded by the USDA, Cooperative State Research Service, Competitive Research Grants Office. Our primary objective in this study is to identify and evaluate technical innovations that will improve the fire resistance of wood truss systems without involving protective membranes. Secondary objectives are to refine the fire endurance model, expand the data base on the high temperature performance of MPC, and expand the data base on performance of fire resistive coatings on wood.

The fire endurance of a structural assembly depends on the combined action of individual trusses, connected by sheathing, that share in carrying the load. System effects (as opposed to single component behavior) generally add safety to an assembly through load redistribution mechanisms. The current single truss model will be expanded to a system model with funding provided by the National Forest Products Association. This will add the contribution of attached wood-based or gypsum sheathing materials to the residual capacity of the assembly. This includes the composite action of the sheathing as well as the load sharing effects within a system of trusses.

Continued research is also needed to develop acceptable heat transfer models for wood assemblies as well as solid wood. The determination of the temperature distribution within the wood components has become a critical item in development of fire endurance models.

SUMMARY

A theoretical model and a user-friendly computer program were developed for predicting the fire endurance of a metal-plate-connected wood truss. Extensive component fire testing was conducted to develop the necessary input and sub-models for thermal degradation of the wood members and the connections. The model was evaluated using existing ASTM E 119 test data. Reasonably good agreement was obtained. The model will be used in a current study to identify the critical factors in the fire endurance of trusses and help develop improved fire resistant wood trusses. Since the ASTM E 119 test method that governs fire endurance regulation of structural assemblies is a test of an assembly, the current single truss model will be expanded to a system model.

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