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Investigation of Behavior of Cold-Formed Steel Sheeting Systems in Fire using Finite Element Modeling

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Abstract

A 3D Finite Element (FE) model of steel sheeting, which includes the screw connector and support plate, is created to investigate the behavior of both steel sheeting and connections at elevated temperatures. The created model considers the material nonlinearity, large deformation and contact behavior. The material damage model for sheeting steel is defined so that the FE model is analyzed through the elastic and plastic ranges up to failure. The FE model is used to predict the ultimate resistance and deformation. The current FE model captures the main behavior of steel roof systems well up to around 20 minutes according to the test results from the literatures. The comparisons to the FE model with connector elements created previously show that the lower stiffness of connections reduces both the mid-span displacement up to 15 min and the compressive forces developed at support because of the restrained thermal elongation, which benefits both steel roof sheeting and connections at support. However, the current model needs to be improved in order to have the same final failure mode as from the test results from literatures.

Introduction

Profiled steel sheeting can be connected to the top chord of its supporting steel roof truss through self-tapping screws. Previous researches (Lu et al. 2008) have indicated that steel sheeting can have a substantial fire resistance by developing catenary action in large deformation if the connections have enough strength. When creating FE model for steel sheeting in fire, it was assumed that no failure has occurred in the connectors by using connector elements that are provided in ABAQUS (2009). In the subsequent researches, the design equations for screwed connections at both room and

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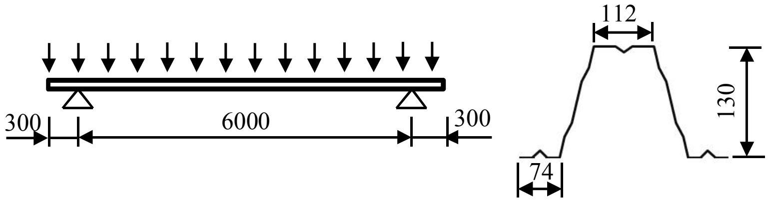
elevated temperatures have been proposed (Lu et al. 2011) based on the single lap shear tests and on the parametric FE analyses for single lap shear connection. Besides, the tests for studying the behavior of screwed connection at elevated temperatures from other researches (Yan and Young 2011) were carried out based on the one direction shear tests. The connection resistance from these researches is then compared to the tensile force when the steel sheeting is in catenary action to verify the capacity of the screwed connections in fire. However, when the screwed connectors are used to connect steel sheeting to its supports, the connectors are first in compression because of the restrained thermal expansion and then in tension because of the catenary actions. The one direction shear tests cannot represent the two-direction behavior well. Therefore, it is necessary to investigate the behavior of both sheeting and screwed connectors at elevated temperature when the screw is integrated into the roof sheeting systems.

In this paper, a 3D Finite Element (FE) model of steel sheeting including single lap-shear connection model is created to investigate the behavior of both steel sheeting and connections at elevated temperatures. The created model considers the material nonlinearity, large deformation and contact behavior. The material damage model for sheeting steel is defined so that the FE model is analyzed through the elastic and plastic ranges up to failure. The model is used to predict the ultimate resistance and deformation in both connections and steel sheeting in fire. In addition, the results from this FE model are compared with steel sheeting model created previously (Lu et al. 2008) when the screws are modeled with connector elements.

FE modeling

Geometry of Structural Systems

The studied roof sheeting is assumed to be a single span structure with span length of 6 m as shown in Figure 1 (a). The length of overhanging at both ends is 300 mm. The load applied to the sheeting is 1.3kN/m^2, which is calculated as the combination of permanent load and snow load with combination factors taken from EN 1990 (2002). The dimensions of sheeting profile for one fold are shown in Figure 1 (b).



(a) Single span sheeting with applied loads (b) Sheeting profile

Figure 1 One-span steel sheeting and its profile for one fold.

Figure 2 shows the structural assembly of roof sheeting and connection details in current FE model. Profiled steel sheet with thickness of 0.8 mm simulates the roof sheeting. Only half rib with half span of steel sheet is modeled because of computing efficiency. The thicker plate with 5 mm thickness represents the top chord (structural hollow section) of a roof truss to which the sheeting is connected. One screw connector ϕ 5.5 mm x 26 mm with head diameter 11 mm is used to connect thin sheet and thicker plate. The built-in steel washer with diameter 15 mm is used between the screw connector and thinner sheet. The detailed connection model as shown in Figure 2 is taken from the previous research (Lu et al. 2008).

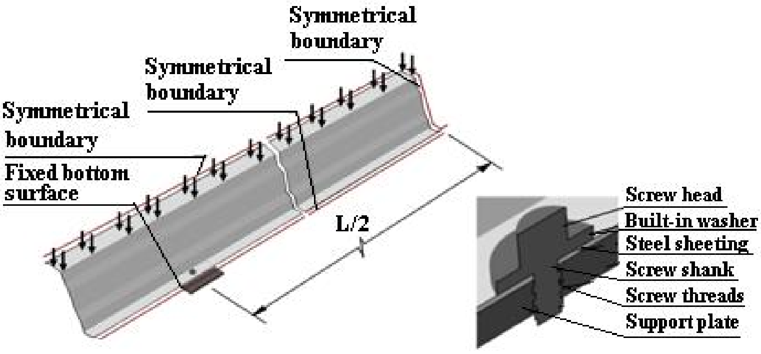
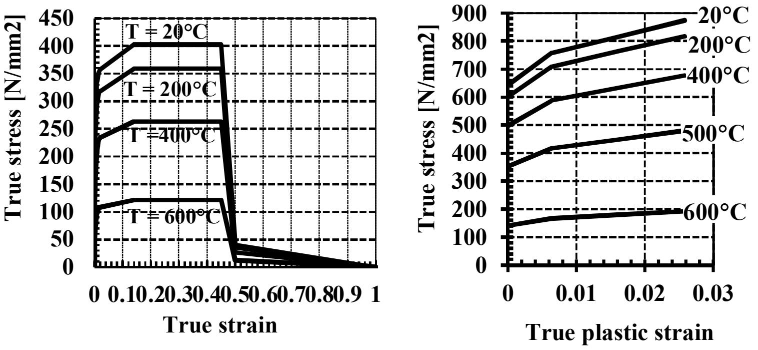


Figure 2 FE model of steel sheeting system and connection details

Commercial FE software, ABAQUS Explicit, is used as an analysis tool. Three dimensional eight nodes solid elements with reduced integration point (C3D8R) are chosen for modeling the thicker sheet, the thinner sheet, the screw, the screw thread and the washer. This element type is in the element library suitable for ABAQUS/Explicit analysis. Because of only one integration node in the thickness direction, instead of one layer of elements, more layers of elements are used along the thickness of thicker and thinner sheets.

Material Modelling

The material of steel sheeting is S350GD+Z275 with the nominal yield strength 350 N/mm^2. Material stress-strain curves are defined according to EN 1993-1-2 (1995) in general and transfered to true stress-strain curves up to engineering strain 0.15. According to Shanley (1957) and our experiences (Lu et al. 2008), the onset of failure strain for steel is usually 0.45 (true plastic strain) instead of 0.15 (engineering strain). At 0.5 plastic strains the damage reaches to 90%. After that, the material completely failed at plastic strain 1.0. The true stress and true strain curves with damages defined above are shown in Figure 3 (a). The material of thicker plate is S355 with nominal yield strength 355 N/mm^2. Previous researches (Lu et al. 2011) have shown that in the joint area, the damages mainly concentrated on the steel sheeting. Thus, no damage has defined in the material model for the thick plate steel S355. Since no material properties for screws at elevated temperature have been found, the material properties for bolt 8.8 given in EN 1993-1-2 (1995) have been chosen in the FE model. The true stress - plastic strain curves are given in Figure 3 (b). Previous researches (Lu et al. 2011) have shown that the failure is mainly bearing failure of thin sheet near screw connection area. Therefore, no damage has defined in the material model for bolt 8.8.

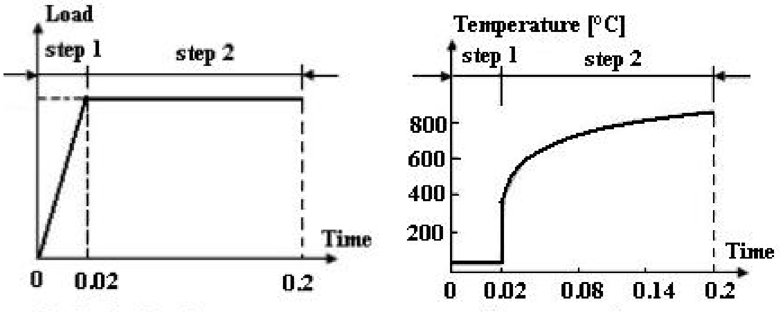


(a) Steel S350 (b) Bolt 8.8

Figure 3 Material models at both room and elevated temperatures.

Loading step

The analysis is carried out in two steps: the mechanical loading was applied first (step 1), and then the temperatures were increased to the given temperture based on ISO standard fire curve (step 2) as shown in Figure 4. The quasi-static analysis procedure was adopted with a small enough dissipated energy fraction so that the energy fraction has no effects on the deflection behavior of sheeting. Generally, it is safe to assume that performing an analysis in the natural time for a quasi-static process will produce accurate static results. However, the computing time is not acceptable. Therefore, the loading rate is applied to the FE model so that the computing procedure finishes in less time and dynamic effects on the model remain insignificant. The ending time for step 1 and step 2 are selected as 0.02 s and 0.2 s, respectively, in the analysis (Figure 4).



Mechanical loads to structure

Temperature increase

Figure 4 Applied load and temperature increase to the structure.

FE results

Figure 5 shows the deformation histories of sheeting with the increasing of temperatures. Because of the degradation of material stiffness, the heavy loaded upper flange deforms more largely than web and lower flange especially at mid span (t = 3 min and t = 9 min). At t = 15 min, the profile at support collapses and at mid span only part of the web works together with the lower flange. Large deformation of the sheeting has been observed along the span. At t = 18 min, the profiled sections both at support and at mid span have transformed to a simple sheet. After that, when the sheeting extricates from the washer, the failure of sheeting has been observed. This failure mode is not the same as observed in earlier tests (Sokol et al. 2006). The reason is due to the simplified material damage rule being defined in material models. The failed elements have been removed from FE models after the damage criteria have satisfied. This differs from the laboratory tests, in which the failure happened gradually because the steel is ductile material. Further improvements in the FE model are needed.

Figure 6 shows the variations of local deformation of joint area with the increasing of temperatures. In order to see the deformation clearly, the screw head and the built-in washer have been removed on purpose from the result visualization. Because of the restrained thermal expansion, the compressive forces are generated first. The steel sheeting is directly bearing to the screw shank to the right. The bearing failure of steel sheeting has been observed at t = 3 min. At t = 9 min, the compressive force reaches the maximum value and deformation of sheeting reaches the maximum. After that, because of the large deformation of sheeting, the compressive forces are transformed to the tensile forces. The bearing of the steel sheeting to the screw shank is now to the left., which can be seen from Figure 6 when t =

15 min. At t = 18 min, the profiled sheeting section has transformed to thin steel sheet. This collapse of cross-section causes extrication of steel sheeting from screw washer because of the possible reason mentioned above.

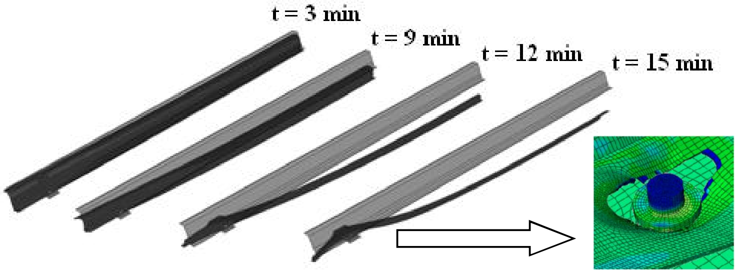
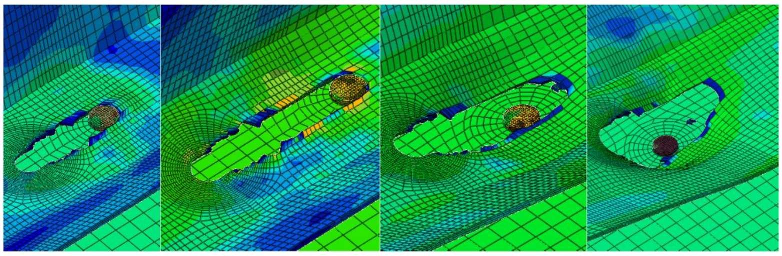


Figure 5 Deformation histories of sheeting.



t = 3 min t = 9 min t = 15 min t = 18 min

Figure 6 Deformation of joint near screw connector without showing screw head and washer

Figure 7 shows the comparisons of displacement-time curves for the mid-points on upper flange, web and lower flange for models with connector elements to those with screws being modeled. It can be seen that for both models initially the profiles deformed as a whole profile. With the increasing of temperature, the stiffness of the material reduced, the upper flange, the web and the lower flange deformed separately. In large deformation, the profiled cross-section collapsed and behaved as simple sheeting. Because the load is applied on the upper flange, the displacement of upper flange is larger than the others.

When the screws are modeled with connector elements, it is assumed that the connector is rigid. It can be seen that the buckling of the sheeting occurred at about 2 to 3 minutes. This is due to the high compressive forces developed because of the restrained thermal elongation. When the screws are modeled with real dimensions, the buckling of sheeting delayed up to about 18 to 19 minutes. The local deformations of sheeting near connector area reduce the value of compressive force. This benefits the sheeting systems.

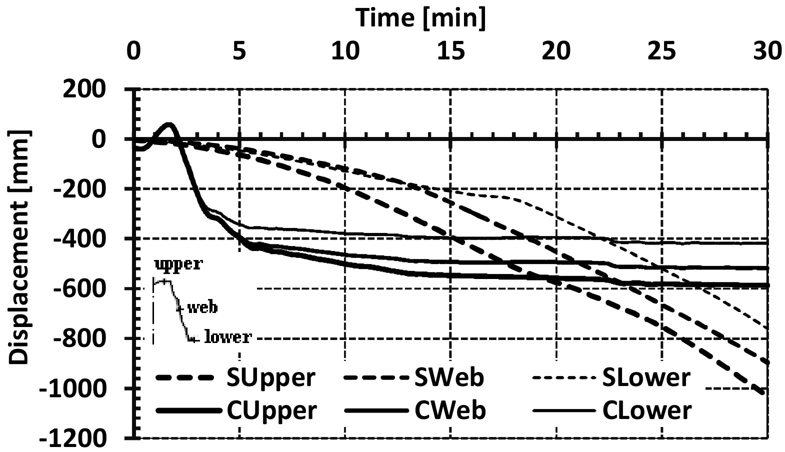


Figure 7 Comparisons of deformation-time curves of model with connector elements and those with screw.

Figure 8 shows the comparisons of horizontal reaction force and time curves for the models with screws being modeled with connector elements and with actual screw dimensions. For both models, the compressive forces are initially observed because of the restrained thermal expansion. Then these compressive forces transformed to tensile forces because of the large deformation. As mentioned before, when the connector elements are used, it is assumed that the sheeting is connected to its support with rigid connection. Therefore, the larger compressive forces are developed than those when the actual screw dimensions are used. When the sheeting buckles suddenly under these higher compressive forces, the transformation from compressive forces to tension forces occurs suddenly (t = 3 min). Because of the lower stiffness of the connection when the actual dimension of screw connection are used, the transformation of compressive force to tensile force happens gradually (at t = 9 min).

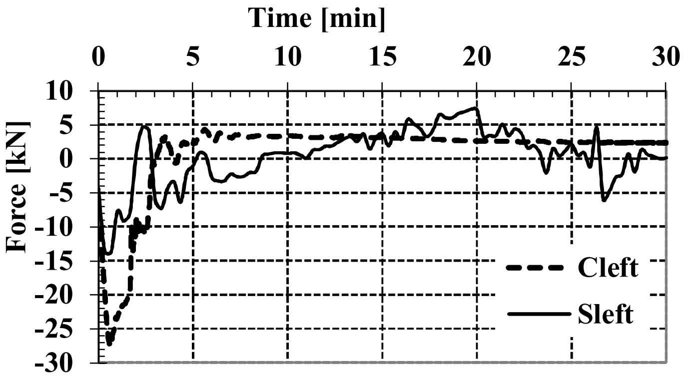


Figure 8 Comparisons of force-time curves of model with connector elements to those with screws.

Conclusions

3D FE model including the actual screw dimensions has been developed to investigate how the roof sheeting behaves in fire. This model includes the damage model of sheeting material. The current model captures the main behavior of steel roof systems well up to around 20 minutes.

The comparisons of current FE model to that with screws being modeled with connector elements show that the lower stiffness of connections reduces both the mid-span displacement and the compressive forces developed at support coming from the restrained thermal elongation, which benefits both steel roof sheeting and connections at support. This observation is valid up to 15 min.

FE model needs to be improved in order to have the same final failure mode as in the tests from literatures. The possible improvements include redefining the material damage criteria and lowering the temperatures of components near the connection area.

Acknowledgements

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