BEHAVIOUR OF COLD-FORMED Z-SHAPED STEEL PURLIN IN FIRE

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ABSTRACT

Great deals of researches on steel beams in steel framed structures have indicated that a steel beam can have a substantial fire resistance in catenary action at large deformation. However, few researches are available for investigating the behaviour of cold-formed steel purlin in fire. A 3D finite element model incorporating both geometric and material non-linearity is created to investigate the behaviour of cold-formed Z-shaped steel purlin in fire. It has been shown that due to the thinness of the material and degradation of the material properties at elevated temperature, the profile buckles locally under restrained thermal expansion in early stage. In the large deformation, tensile forces developed in steel purlins to resist the transversely applied load. The steel purlin can survive in fire via catenary action. Comparing to one-span purlin, two-span purlins have less in-web-plane deformation due to the capability of mid-support but with larger out-of-web-plane deformation due to the sudden lateral-torsional buckling. The earlier inelastic buckling at two end supports in one-span purlin actually helps reduce the compressive forces developed due to restrained thermal expansion. However, the maximum axial tension forces developed at the supports are the same for both one-span and two-span purlins.

Key words: cold-formed steel, Z-shaped purlin, structural fire design, catenary action, FE modelling

INTRODUCTION

Traditionally, the resistance of steel beam in fire is calculated according to flexural bending behaviour with small deflection and without considering the effects of end axial restraints. This practice of evaluating fire resistance of the beam is based on standard fire tests on a simply supported individual beam. In real structure, the surrounding members restrain the beam both axially and rotationally. With the presence of axial constraints, the beam will behave in catenary action at large deflection stage. The catenary action is a load carrying mechanism where the bending moment capacity of the beam is negligible but the beam will still be able to resist the applied transversal load with the tension force developed in the beam via further deflection even with reduced material strength (Usmari e.t.al., 2001, Yin and Wang, 2004, Wong, 2005, Wang and Yin, 2006). If large deflection is acceptable in practice, the fire protection might be unnecessary or reduced.
Cold-formed steel purlins have been widely used in industrial buildings to act both as a secondary beam to support the roof sheeting and as the bracing member to stabilize the main frame structure. Currently, few researches have been available on the investigation of the behaviour of cold-formed steel purlin in fire. In this paper, a 3D finite element model incorporating both geometric and material non-linearities is created to investigate the behaviour of cold-formed Z-shaped steel purlin in fire. The model has been used to understand the failure mechanism of the purlin and further to investigate the effect of the number of spans on the behaviour of the purlin.

FINITE ELEMENT MODELLING

Geometry

The roof construction with a lightweight purlin in this research is composed of a Z-shaped purlin and a sandwich panel. The sandwich panel is connected to the top flange of the purlin with a roof screw at panel crest. The purlin is bolted to U-shaped steel consoles, which are in turn welded to the supporting members. The structural details of sandwich-purlin systems and its connections to the supporting truss are shown in Fig. 1. The dimensions of Z-shaped steel purlin and U-shaped steel console are shown in Fig. 2.

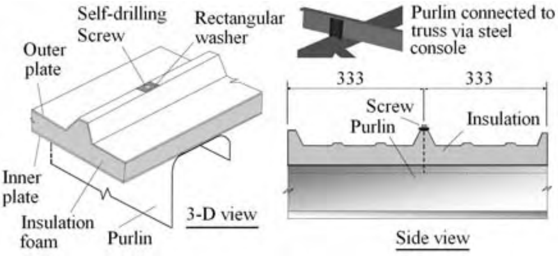


Figure 1. Crest-fixed sandwich-purlin systems.

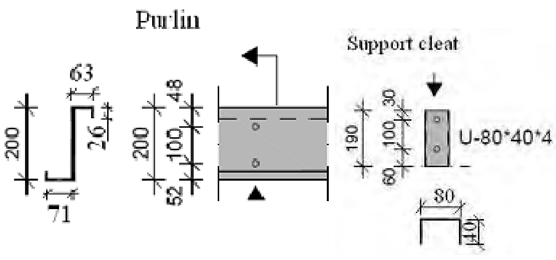


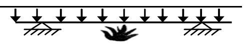
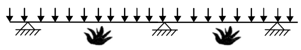
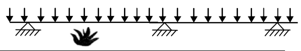
Figure 2. Dimensions of purlin and steel console.

The thickness of purlin is 2 mm and the span length of the purlin is 6 m. The distance between the screw connectors is 333 mm.

Three FE models have been created according to the number of span and heating conditions as shown in Table 1. Model 1Span is the model for one span purlin exposed to fire; Model 2Span2Heat is the model for two-span purlin and both spans exposed to fire; and Model 2Span1Heat is the model for two-span purlin but with only one span exposed to fire.

Table 1

FE models

Models	Heating span	Span no.
1Span	1	
2Span2Heat	2	
2Span1Heat	1	

FE meshes

Fig. 3 shows the FE model of a single span sandwich purlin system. The model is composed of steel purlin, steel console and steel sheeting, which is used to simulate the inner plate of the sandwich panel. Commercial FE software, ABAQUS/Explicit (2009), is used as an analysis tool. The quasi-static analysis procedure was adopted. Thin shell elements with reduced integration S4R are used to model purlin, steel sheeting and steel consoles. Three dimensional connector elements with 2 nodes (CONN3D2) are used to simulate the connections between the sheeting and purlin, and between the purlin and steel consoles. The connection-type of the connector elements according to ABAQUS is a BEAM, which provides a rigid beam connection between two connected nodes, and imposes kinematic constraints. The general contacts have been defined among the contact surfaces in the whole FE models.

Material properties

The steel grades of steel purlin and steel sheeting are both S350GD+Z. The stress-strain curves at elevated temperatures without strain hardening given in EN 1993-1-2 (2005) have been used and have been transformed to true stress and true strain curves. The reduction factors for yield strength at elevated temperature are taken from EN 1993-1-2 Annex E and reduction factors for modulus of elasticity are taken from the main text of EN 1993-1-2. It is assumed that the material properties of the console steel are not affected by the increasing of temperature. The steel grade of the steel console is S355. Thermal elongation of steel at high temperature is defined as stated in EN 1993-1-2. Density of steel is 7850 kg/m^3 and modulus of elasticity is 210 000 N/mm^2.

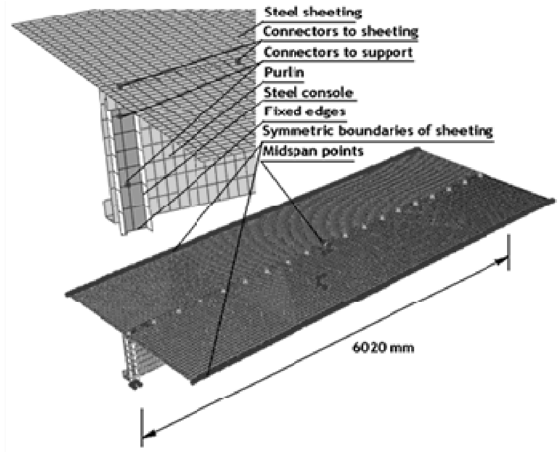


Figure 3. FE-modelling of single span purlin.

Loading and boundary conditions

The two-step analysis is carried out, in which the mechanical loading (0.73 kN/m^2) was applied first (step 1) and then the temperatures were increased according to the nominal fire curve (step 2). It is assumed that in the models, the temperatures are uniform in steel purlin and steel sheeting. In FE models two steel consoles are clamped along the welded edges, and along span length the symmetric boundary conditions are defined for steel sheeting (Fig.3). Two types of outputs are required from FE models, i.e., the displacements of the given nodes of the cross-section at mid span, and the reaction forces at the fixed edges of the steel consoles (Fig.4).

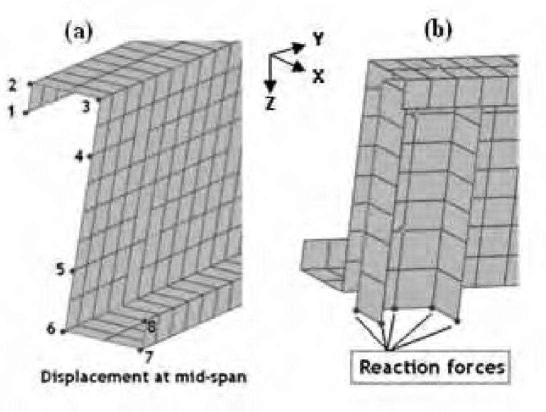


Figure 4. Output details in FE model.

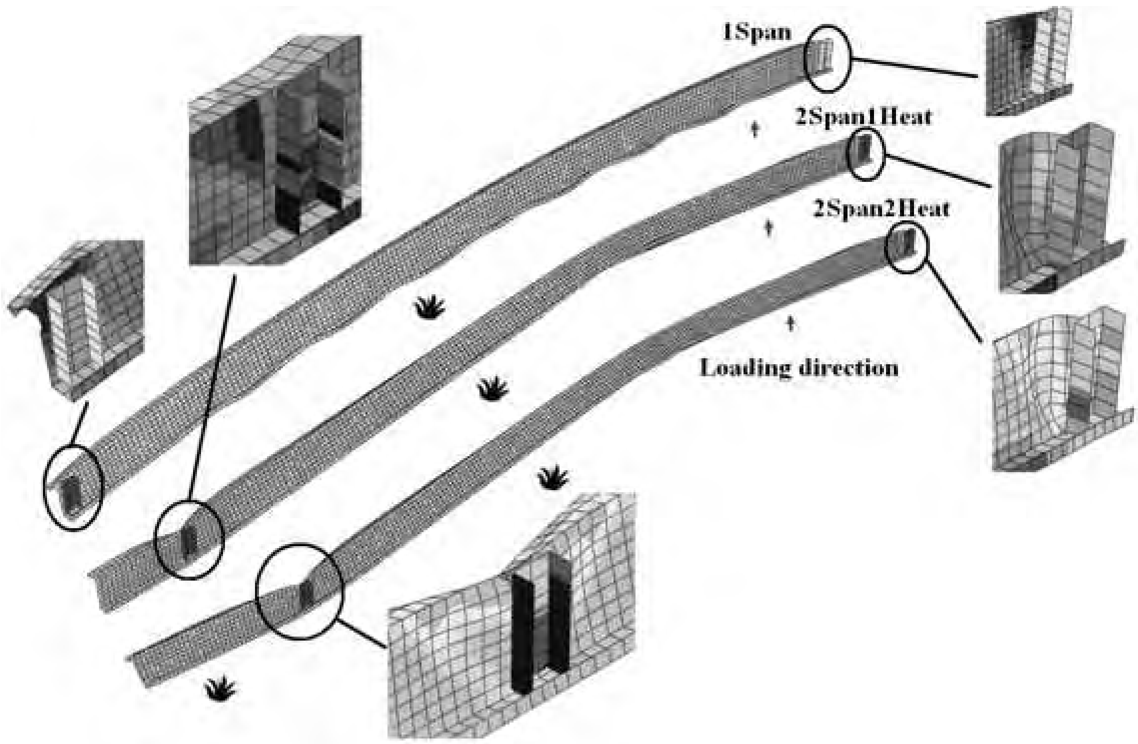


Figure 5. Deformed shapes of purlin systems.

ANALYSES OF FE RESULTS

Deformed shape

Fig. 5 shows the deformed shapes of purlin systems at 603 °C for three models respectively. For Model 1Span, multiple-wave local buckling of the purlin lip located at the loading side has been observed. This is the result of the joint influences of both the compression forces coming from the restrained thermal expansion and the mechanical loading applied to purlin via steel sheeting. For Model 2Span1Heat, local buckling of the purlin lip is first observed at the place with the maximum sagging bending moment. Then the inelastic buckling at mid support occurred at free flange of the purlin near the support. Finally, the sudden lateral-torsional buckling of the purlin happened when the temperature is at 490 °C. When comparing to model 2Span1Heat, the Model 2Span2Heat has the similar deformed shape. However, the lateral-torsional buckling occurred at 480 °C. Besides, the deformation of the Model 2Span2Heat happened at both spans whereas the deformation of the Model 2Span1Heat occurred only in the span exposed to fire.

Out-of-web plane displacements

Fig.6 shows the comparisons of out-of-web-plane deformation of the point 6 of the cross-section at mid-span for three models. Due to the similar deformed shapes at right supports (Fig. 5) for three models, the initial out-of-web-plane deformations have been observed at temperature of 184 °C for the Model 1Span and 123 °C for both the Model 2Span1Heat and Model 2Span2Heat. Because of the different deformed shapes at left/mid supports (Fig. 5) and different heating conditions, the Model 2Span1Heat has sudden out-of-web-plane deformation at around 490 °C while the Model 2Span2Heat at around 480 °C. However, no sudden out-of-plane deformation has been observed for the Model 1Span. The out-of-web-plane deformation for the Model 1Span increases further after the inelastic buckling at the end supports and multiple-wave local buckling of the restrained flange and lip. Therefore, the Model 1Span has a smaller out-of-web-plane deformation comparing to two-span models after their sudden out-of-web-plane deformation.

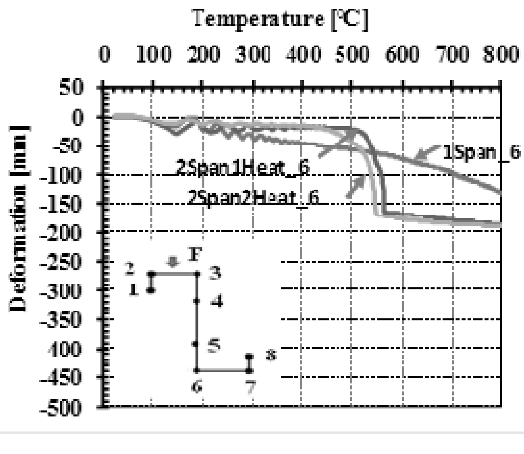


Figure 6. Displacement temperature curves (out-of-web plane).

In-web plane displacements

Fig. 7 shows the comparisons of in-web-plane deformation of the point 3 and point 6 of the cross-section at mid-span for the above-mentioned three models, respectively.

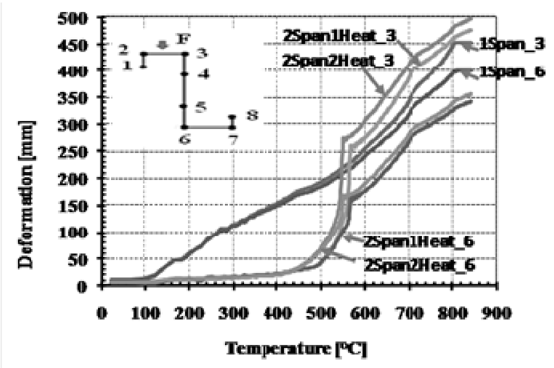


Figure 7. Displacement temperature curves (in-web plane).

It can be seen that the in-web-plane deformation is increased at around 184 °C for the Model 1Span due to the early inelastic buckling of both end supports. However, no big increases were observed in the deformations for two-span models before sudden lateral-torsional buckling at around 490 °C for the Model 2Span2Heat and at around 480 °C for the Model 2Span1Heat because of mid-supports. At the same time, the original Z-shaped cross-sections fall down and bend in minor axis. For the Model 1Span, due to local buckling of the flange restrained by steel sheeting, the point 3 and 6 deformed separately at already 200 °C.

Reaction forces developed at supports

Fig. 8 and Fig. 9 show the developed axial forces at the fixed edges of the steel consoles at right and left/mid supports for three models. It can be seen that for all models, the axial forces developed at the right end supports are initially compressive due to the restrained thermal expansion; then transferred to tensile forces when the purlins are in catenary actions. It can be seen that the maximum compressive forces occurred at the temperature of 123 °C for two-span models and 184 °C for the one-span model, and then the forces decreased. This decreasing is caused by the inelastic buckling at the right end supports. For the Model 2Span1Heat and Model 2Span2Heat the second force decreasing occurred at the temperature a little less than 500 °C. The second decreasing is due to the inelastic local buckling at mid supports and lateral-torsional buckling of purlin. In addition, the compressive forces are transferred to tensile forces at around 511 °C for the one-span model, at 561 °C for the Model 2Span2Heat and at 544 °C for the Model 2Span1Heat.

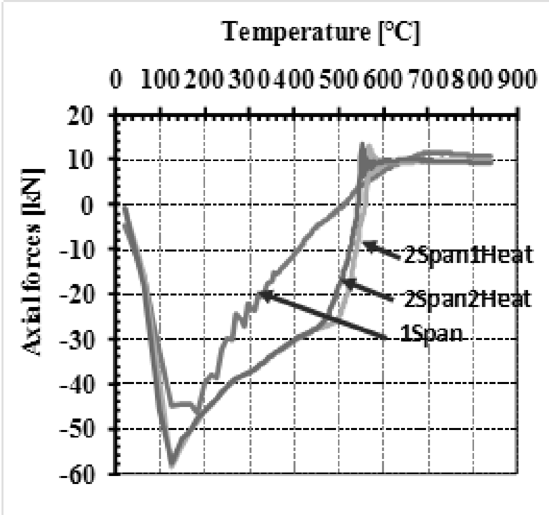


Figure 8. Axial forces developed at right support.

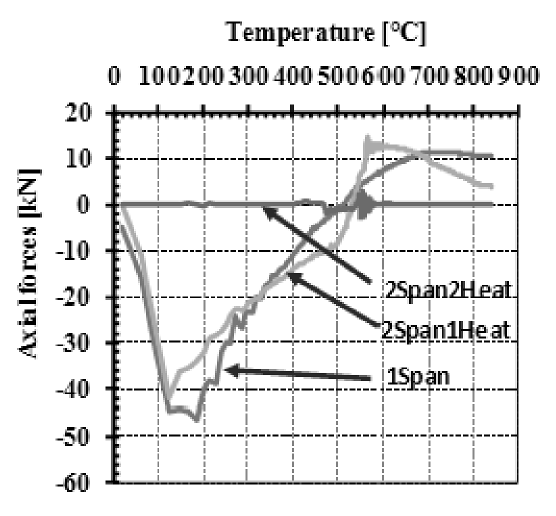


Figure 9. Axial forces developed at left support.

CONCLUSIONS

The compressive forces developed initially at the supports due to the restrained thermal expansion. The maximum value has been reached at about 184 °C for the one-span model and 123 °C for two-span models. Due to inelastic buckling of the purlin at the end supports, the compressive force was decreased. At 511 °C for the Model 1Span, at 544 °C for the Model 2Span2Heat and at 561 °C for the Model 2Span1Heat, the axial forces changed from compression to tension, the purlins were in catenary action. This behaviour was observed for all models.
The purlin heated from two spans behaves similarly to the purlin heated from only one span. The sudden out-of-web-plane deformation occurred at about 10 °C earlier for the purlin heated from both spans. In addition, the axial reaction forces at the mid-support are zero for the purlin heated from two spans

because of the symmetry of structures.

When comparing to one-span purlins, two-span purlins have smaller in-web-plane deformation due to the mid-support. However, two-span purlins have larger out-of-web-plane deformation due to sudden lateral-torsional buckling. As far as the reaction forces at support are concerned, the earlier inelastic buckling at two end supports in one-span purlin actually helps reduce the compressive forces developed at the end supports. However, when the purlins are in catenary action, the maximum axial tension forces developed at the supports are the same for both one-span and two-span purlins.

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