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Temperature-induced Instability in Cold-formed Steel Beams with Slotted Webs Subject to Shear

M.Z. Naser[1], N.V. Degtyareva[2]

1.0 ABSTRACT

Cold-formed steel (CFS) is an emerging construction material that has been gaining momentum over the past few years. While the behavior of structural members made of CFS has been extensively studied at ambient conditions, the performance of these members under extreme events such as that associated with fire, is yet to be understood. In order to bridge this knowledge gap, this paper presents outcome of numerical studies aimed at understanding fire response of CFS beams. More specifically, this study explores the effect of temperature-induced shear-based instability on response of C-shaped CFS beams with slotted webs. For studying this phenomenon, a three-dimensional nonlinear numerical model is developed using the finite element (FE) simulation environment; ANSYS. The developed FE model is designed to incorporate temperature-dependent material properties as well as to account for unique geometric features and restraint conditions, as to accurately trace thermal and structural response of CFS beams. Once validated, the developed model was utilized to examine the effect of a number of factors namely; channel depth, web perforation pattern, as well as boundary conditions, on temperature-induced buckling susceptibility of CFS beams. The obtained results showed that these examined factors can significantly affect shear response of CFS channels with slotted webs at elevated temperatures. Findings observed from FE simulations were also shown to agree with that obtained from

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especially derived design expressions that give due consideration to geometric features and temperature-dependent material properties of slotted webs. This study concludes that in order to accurately capture the response of fire-exposed CFS beams, an accurate presentation of geometric and material features in such members is essential.

Keywords: Cold-formed steel (CFS); Buckling; Slotted webs; Fire resistance; Shear capacity; Finite element modeling.

2.0 INTRODUCTION

As demands for lighter, leaner, and more adaptable constructions continue to grow, there is a realization and need for integrating novel construction materials with adequate strength, ductility, and durability [1]. One such building material is cold-formed steel (CFS). CFS offers unique solutions that could potentially outperform traditional construction materials whether from economical or structural points of view [1, 2]. For a start, structural members made of CFS have favorable strength-to-weight ratio, high quality control, and can be efficiently produced through an energy-saving cold forming process. Other advantageous also include ease of handling, quick installation and simple erection [3, 4].

A common feature of CFS structural members is that they are relatively slim and often come in thin and solid sections. As a result, these members are usually classified as "slender" in North American standards (such as AISI [4]), or as "class three or four cross-section" in European standards [5]. This slenderness is much higher than that of typical hot-rolled steel sections, and hence, CFS sections are vulnerable to failure through buckling (i.e. inelastic shear buckling or elastic shear buckling mode - depending on web slenderness) [6, 7]. Buckling of CFS sections is often triggered through shear-induced instability and hence CFS beams have been shown to be sensitive to shear loading [8]. An interesting point to note is that in order to further optimize (reduce) overall weight, as well as improve their thermal insulation performance, CFS sections with slotted webs have been recently produced [3, 4]. From the point of view of this study, the integrated slots add a number of complexities that may not arise in the case of solid CFS sections, such as; 1) reducing overall sectional rigidity, 2) non-uniform distribution of material stiffness which can shift section centroid along the length (span) of a CFS beam, and 3) non-uniform temperature distribution as well as thermal gradients which can initiate thermal bowing [8, 9].

While derivatives of Effective Width Method (EWM) and the Direct Strength Method (DSM) could be used to evaluate flexural behavior of CFS beams made with open and closed cross-sections, there is very limited guidance into evaluating shear response of CFS beams with slotted webs [10, 11]. This has been pointed out in a recent study carried out by Degtyarev and Degtyareva [10]. These researchers reported a substantial reduction in ultimate shear strength of web-slotted CFS channels when compared to solid channels. In pursuit of developing design guidelines, Degtyarev and Degtyareva [10-13], among others [14-16], modified existing calculation approaches and also proposed new design expressions derived from experimental observations and analysis of numerical studies.

A closer examination to the natural slenderness of CFS structural members reveals that, and just like their closest counterpart those made of hot-rolled steel, CFS beams can be vulnerable to thermal loading (fire). Under fire conditions, structural members experience temperature rise causing deterioration in strength and modulus properties of constituent materials which translates

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into losses in flexural and shear capacity and eventually failure. The time to reach this failure is often referred to as fire resistance. The required fire resistance (fire rating) for various structural members and components is listed in building codes; such as International Building Code (IBC), as well as testing agencies (namely Underwriter Laboratories). Surprisingly, fire rating is solely evaluated based on flexural limit state without any consideration to shear or instability limits. This is in contrast to ambient temperature design philosophy, where a beam is generally designed to satisfy flexural limit state and then checked for shear resistance, stability and serviceability requirements [17].

Although deriving failure based on flexural limit state is a valid notion in common bending-dominant loading scenarios, it still may not be representative in certain situations where shear forces are high or in the event where shear capacity degrades faster than flexural capacity. Shear forces can be dominant under particular loading configurations especially with those associated with concentrated (point) loads near ends of beams connecting columns in buildings [17]. Another case where shear can govern is in beams with reduced cross-sectional area (slotted or coped webs). Recent fire experiments also noted that shear capacity in beams with slender webs, degrades at a much rapid pace than flexural capacity [18]. This rapid degradation was triggered by development of temperature-induced buckling effects occurring in solid or cut-through webs [19, 20].

Limited studies have investigated the performance of CFS building elements under elevated temperatures. Much of the published works examined the performance of lightweight structural panels, as in those used in dry walls incorporating gypsum boards [20]. Still, few researchers managed to carry out fire experiments on CFS structural members (i.e. beams and columns). In one study, Liam and Rodrigues [21] reported outcome of fire tests on solid cold-formed galvanized steel beams (with closed built-up sections and open section profiles). In these tests, Liam and Rodrigues [21] explored the influence of cross-section geometry, magnitude of axial restraint, as well as rotational stiffness on the response of fire-exposed simply-supported CFS beams subjected to four point bending. The main outcome of this work noted how all tested beams failed within 20-30 minutes of exposure to the ISO 834 standard fire. These researchers also identified a critical temperature of 700°C to strongly affect simply supported beams. This temperature is much higher than that enforced by Eurocode 3 (given as 350°C). Liam and Rodrigues [21] reported that CFS beams made of closed built-up section achieved an increase of about 50% in failure time when compared to open section beams. A thorough analysis of published works show that much of the published literature, such as that carried out by Gunalan and Mahendran [22], and Cheng et al. [6], also investigated fire response of solid (without slots) CFS beams and columns.

Very little research has been directed towards investigating fire performance of web-slotted CFS structural members (specifically to beams). In one study, Ma et al. [8] numerically studied the fire performance of web-slotted channel columns with non-uniform temperature distributions. These researchers noted how failure modes of web-slotted channels subjected to non-uniform temperature distributions vary with the increase in sectional temperature and how progression of failure tend to be very complex. Compared with solid members, web slots were shown to significantly reduce the ultimate strength of the slotted cold-formed members, especially at higher temperatures in the range of 500-600°C. In another study, Karlström [23] experimentally and numerically investigated the response of solid and slotted studs both at room and under elevated

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temperatures. The main objective of this study was to develop and validate a simple design approach through advanced calculation methods (FE simulations). The developed approach can evaluate fire resistance under various heating conditions.

It can be inferred from the above discussion that the slender nature of CFS sections, when combined with the presence of slots in the web, may significantly hinder the response of CFS beams with slotted webs under fire conditions more so in the event that these members are subjected to high shear loading. Further, the fact that design rules for CFS beams are largely based on past research carried out on solid CFS sections, which been shown to be inadequate for web-slotted CFS sections as noted by few researchers [21], calls for further research in this area. Thus, this study intends at bridging this knowledge gap by developing a highly complex three dimensional (3D) finite element model that incorporates both geometrical and material nonlinearities as well as temperature-dependent material properties in order to accurately trace the fire response of various CFS beams with slotted webs. More specifically, this model aims at examining effects of channel depth, web perforation pattern, as well as boundary conditions and load level on temperature-induced degradation to shear capacity and buckling of channel-shaped CFS beams with slotted webs.

3.0 FIRE RESPONSE OF CFS BEAMS WITH SLOTTED WEBS – MECHANISMS OF FAILURE

In civil structures, beams are predominantly subjected to flexural actions arising from applied loading. As a result, beams are often designed to resist bending effects as well as to satisfy strength (flexural/shear) and serviceability limit states (i.e. deflection and vibration). Pure bending is seldom achieved in typical structures, but rather beams experience a combination of bending and shear. Since shear loading rarely governs the design of beams, it is common for beams to be primarily designed for bending and then checked for shear, stability and serviceability requirements. This practice is commonly followed in the design process at ambient conditions and has been well established in building codes and design guidelines [4, 5].

In the event where fire breaks out in a building, structural members; and from the point of view of this study, CFS beams; experience rapid rise in temperature facilitated by the high thermal conductance of CFS and low thermal mass (provided by thin and light plates). Beams are often subjected to fire from two sides and bottom soffit and as such webs in beams are often exposed to higher thermal (fire) loading; since they are exposed to the fire from two sides (and have larger surface area than flanges). As a result, temperature rise in webs is occurs at a faster pace as compared to that in flanges, especially if the top flange is attached to an inert material such as concrete or gypsum. Hence, strength properties of CFS in the web portion can degrade, in principle, at a higher rate than that in flanges. One strategy to control this rapid temperature rise is to introduce perforations (long narrow slots) into webs. While such slots reduce the amount of solid material available to conduct temperature; (i.e. as air has lower thermal capacity that CFS) and this prolongs heat transfer across the web, these slots also reduce the amount of material available to resist applied loading (bending moment and shear force). In other words, perforations reduce the effective section of a typical CFS beam with slotted webs as compared to that of a solid CFS beam.

The mechanics of force transfer and structural resistance show that sectional capacity is a function of geometric properties (i.e. section modulus, area of section) as well as material properties (i.e. yield strength). The former remains virtually unchanged during fire conditions while the later degrades due to metallurgical changes driven by the rise in temperature. This degradation can be estimated through examining data plotted in Fig. 1. This figure shows degradation in mechanical properties of CFS, and for comparative purposes hot-rolled steel (as recommended by Eurocode 3 [5]). In this figure, the sectional capacity of a CFS beam is expected to reduce to about 53% of its initial capacity once sectional temperature reaches 500°C (as compared to 78% if the beam was made of hot-rolled structural steel). A closer look into this figure also shows that degradation in strength properties in CFS initiates at lower temperature as oppose to that in hot-rolled steel (150°C vs. 400°C). Overall, this figure shows that CFS undergoes much faster degradation in strength properties than hot-rolled steel and as such CFS structural members can be much more vulnerable to premature failure under fire conditions.

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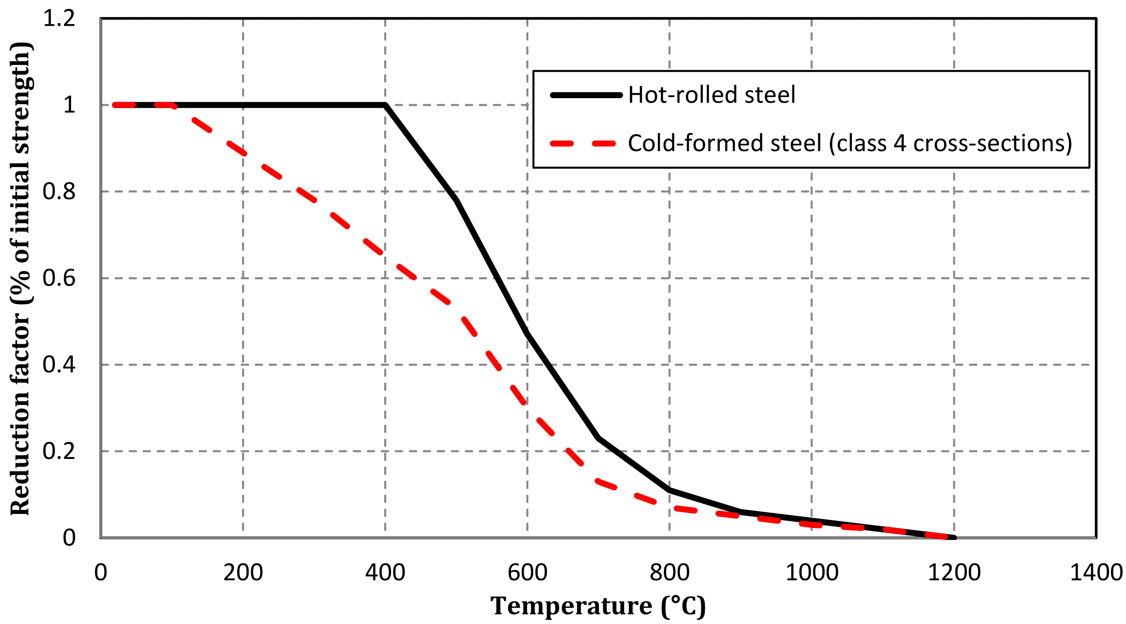

Fig. 1. Reduction factors for strength properties for CFS and hot-rolled steels at elevated temperatures [5]

Following structural engineering principles, a beam roughly fails once its moment (or shear) capacity drops below its bending moment (or shear force) arising from applied loading (i.e. concentrated loads or uniformly distributed loading (UDL)). Since the web is main contributor to shear capacity, shear capacity in beams can degrade at a much higher rate than flexural capacity due to 1) rapid temperature rise in thin web, and 2) lesser web area (due to thin web plate and presence of slots, if any). Fortunately, and although strength degradation is higher in web than flanges, shear force in most scenarios is much smaller than available shear strength. This unlike bending moment where the reserve in moment capacity is relatively smaller than that in shear capacity; as beams are designed (and optimized) to resist bending. Hence, in a typical loading scenario, failure occurs once moment capacity falls below the level of bending moment. This is

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one of the main rationales why current practices seem to associate failure in fire exposed beams with flexural strength limit state alone and without any regards to shear (or instability) limit state.

In the case where a beam is loaded with high shear force, resulting from concentrated loads i.e. supporting columns or walls, shear effects dominate the structural response as bending effects are insignificant. In such a scenario, the state of the naturally vulnerable CFS beams with slotted webs to fire conditions can further worsen. For a start, the reduced size of web (due to presence of slots) offers limited reserve to the rapidly degrading shear capacity. The geometrical features of perforations introduce further complications in terms of developing thermal gradients and weak spots (at points connecting slots) which generate stress concentrations that eventually lead to temperature-induced instability (i.e. shear buckling). Since both of these effects are neglected in room temperature design, such effects can severely damage structural performance of CFS beams with slotted webs and prompt premature and brittle failure under fire conditions. One should note that once temperature-induced buckling occurs, the assumption of virtually constant section modulus is no longer valid.

Such a situation can be better demonstrated through tracing the response of a typical CFS beam from loading stage to failure under fire exposure similar to that shown in Fig. 2. This figure shows a simply supported CFS beam subjected to two different loading scenarios as well as corresponding moment and shear capacity at ambient conditions and during exposure to fire. In the first scenario, the beam is subjected to a uniformly distributed loading (UDL) and as such bending effects govern response of this beam. Thus, failure is expected to occur when the applied bending moment exceeds the moment capacity at the mid-span section as shown in Fig. 2a. This

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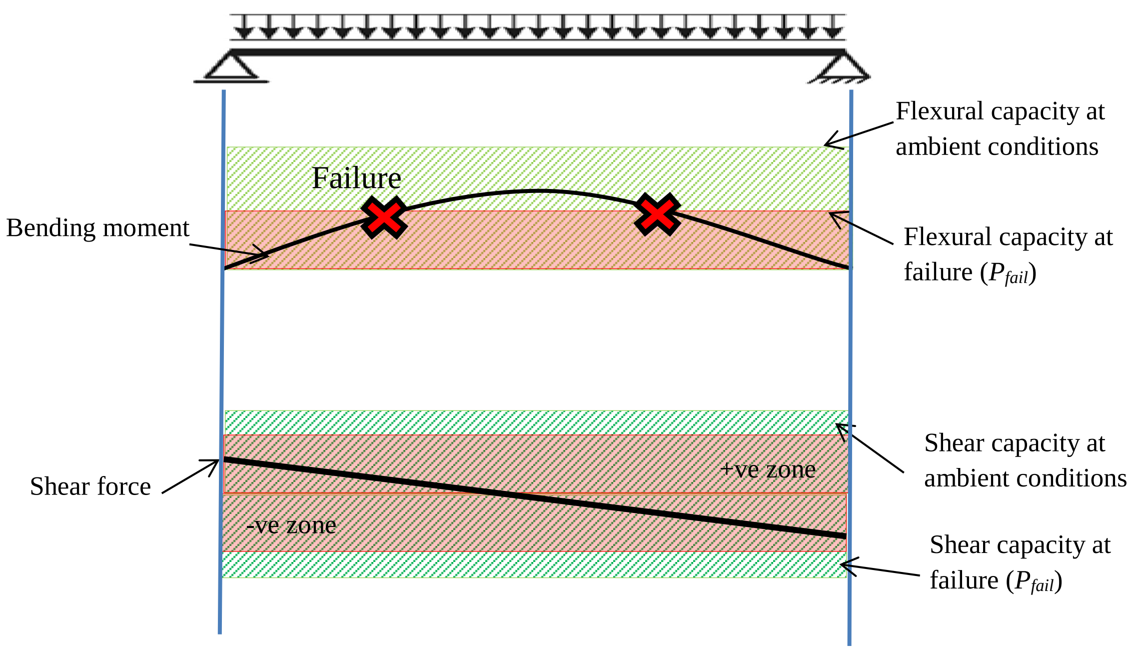
figure also shows how this beam has sufficient shear reserve (shear capacity is higher than applied shear force) even at failure. On the other hand, Fig. 2b shows the same beam but subjected to two heavy concentrated points near the end supports. These two forces result in significant level of shear (as compared to bending moment). Due to this loading configuration, the response of this beam is dominated by shear effects and failure occurs once shear capacity drops below the applied shear force and prior to onset of flexural limit state (since the beam has sufficient reserve moment capacity in this loading configuration). In the case where shear force cause buckling of web, this buckling is expected to induce additional losses to shear capacity, in lieu of those arising from material deterioration, which further accelerates failure of the beam [24]. One should note that once the web panel buckles, the shear load is transferred through diagonally generated tension stresses, and this mechanism is often referred to as tension field action. The higher is slenderness of the webs, the higher fraction of the shear resistance is provided by the post-buckling action.



(a) Beam subjected to dominant bending moment

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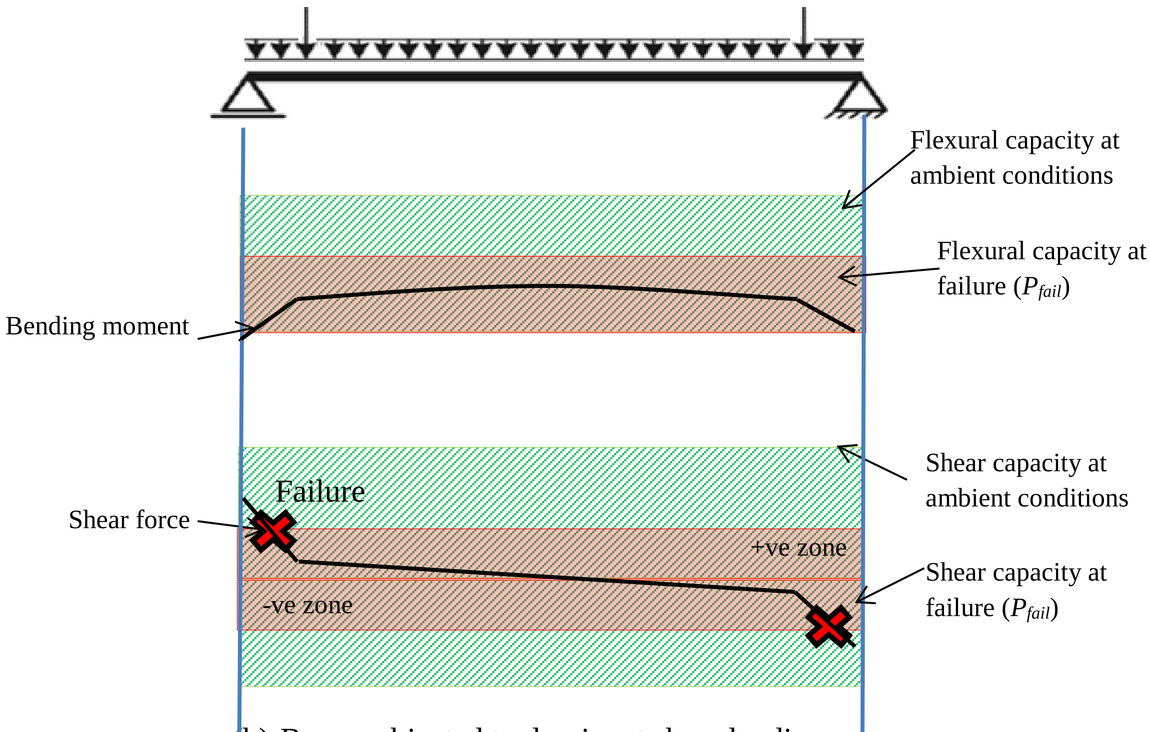

(b) Beam subjected to dominant shear loading

Fig. 2. Variation of bending moment and shear force under different loading scenarios

The above discussion infers that CFS beams with slotted webs can be susceptible to shear failure and temperature-induced instability. This, when compared with the fact that limited work has been carried out over the last few years on shear response of CFS beams under fire conditions, highlights the need for research in this area.

4.0 DEVELOPMENT OF FINITE ELEMENT NUMERICAL MODEL

To study the effect of shear on the response of CFS beams with slotted webs under fire conditions, a finite element model is developed using ANSYS software. For tracing the realistic fire response of beams, several parameters including geometric and material nonlinearities, temperature-dependent material properties and various failure limit states are accounted for in the fire resistance analysis. The main features of the model, including discretization, material properties and failure limit states, are discussed herein.

4.1. Geometry and discretization

The developed three dimensional finite element model has the geometry of typical CFS beams (of channel cross section with slotted web) as shown in Fig. 3. The geometric features of these channels are selected to cover common CFS sections used in construction applications. The thickness of selected channels is 2 mm. The depth of channels is also varied between 150 and 250 mm. The flange widths are 45 and 65 mm for channels with depths of 150 and 250 mm, respectively. All flanges have 13 mm long lips with the inside bend radius of the equal to two base metal thicknesses of the channels. Further, slotted channels with one and two perforated regions are also considered. The 150 mm deep beams had six and eight slot rows for channels with one perforated region and six slot rows for channels with two perforated regions, while the 250 mm deep beams had six, eight and twelve slot rows for channels with both one and two perforated regions. Numbers of perforated regions and slot rows, distance between perforated regions and sizes of perforations, together with other geometric properties of CFS channels, are shown in Fig. 3 and listed in Table 1. Overall, 36 3D models of channels with flat slotted webs are developed and analyzed. These channels are distinguished given the following designation: D-t-L_s-B_{sl}-N-n-BC, where *D*=channel depth (mm), *t*=channel thickness (mm), L_s=slot length (mm), B_{sl}=slot height (mm), *N*=number of perforated regions, *n*=number of rows of slots, *BC*=boundary conditions (*R*=realistic, *TS*=test setup).

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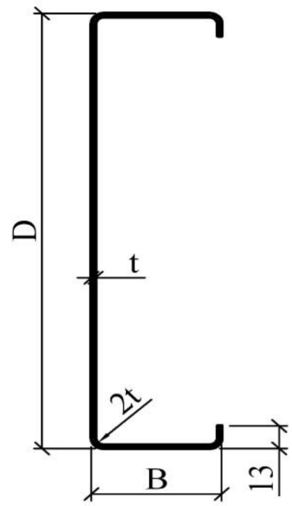
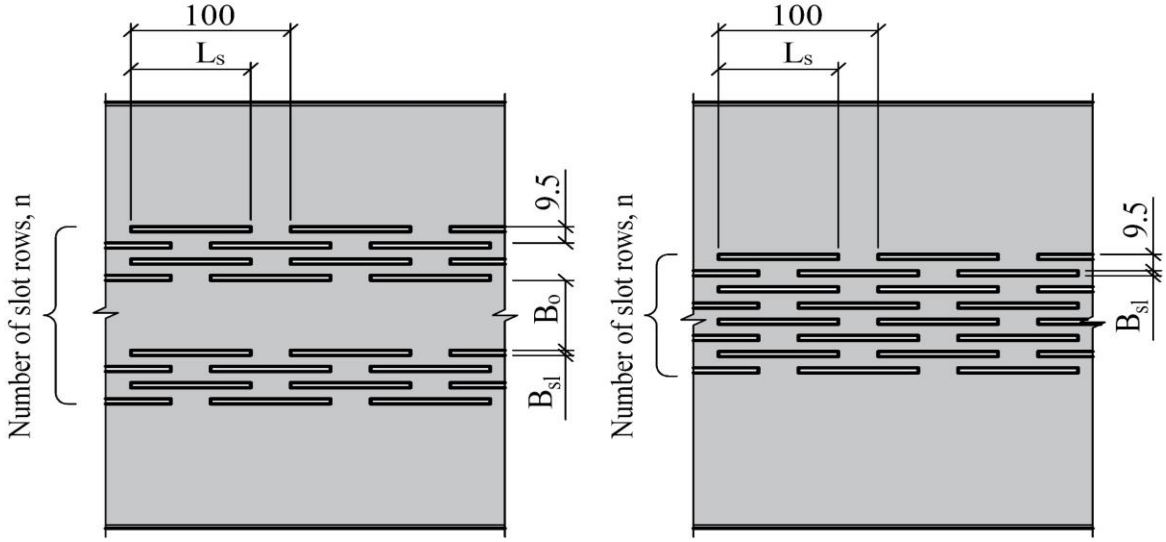


(a) Cross-section dimension and nomenclature



(b) Features of web perforation pattern

Fig. 3. Geometric properties of selected CFS beam with slotted web.

Table 1 Geometric parameters analyzed in CFS beams with slotted webs

D (mm)	**N**	**n**	**L_s (mm)**	**B_{sl} (mm)**	**Boundary conditions**	**Bo (mm)**
150	1	6; 8	60	3	TS; R	-
150	1	6; 8	90	7	TS; R	-

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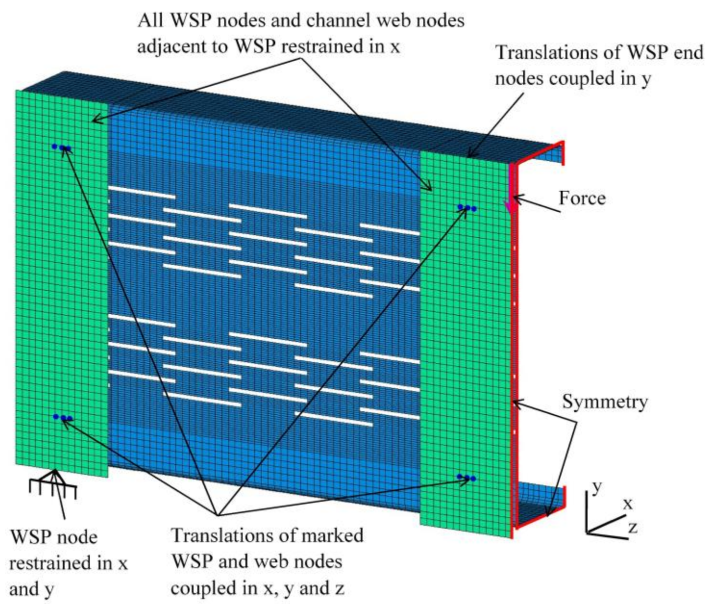
150	2	6	60	3	TS; R	26.5
150	2	6	90	7	TS; R	26.5
250	1	6; 8; 12	60	3	TS; R	-
250	1	6; 8; 12	90	7	TS; R	-
250	2	6; 8; 12	60	3	TS; R	37
250	2	6; 8; 12	90	7	TS; R	37

The finite element analysis was performed in three steps. In a preliminary step, a sensitivity study was carried out in which the discretization (element size) and initial geometric imperfections were extensively studied. The best combination of these effects, i.e. 5 mm element size for non-perforated regions and 1.5 mm for perforated areas (see Fig.4) and a magnitude of D/150 for initial geometric imperfection, were implemented into the developed numerical model herein. Then, the elastic buckling analysis was conducted to obtain the elastic buckling modes. In this step, the lowest elastic buckling mode was arrived at and then used in the nonlinear analysis for modeling the initial geometric imperfections. Then, the transient thermal-stress analysis was performed to obtain cross sectional temperatures (in step 2) as well as stress distribution and failure modes of channels (in step 3). A selected temperature-time curve, with a maximum temperature of 1000°C, was linearly applied over 120 minutes.

In order to model the transient thermal-stress analysis, different thermal and structural element types available in ANSYS elemental library are used. In the thermal analysis, element type SHELL131 was used to simulate heat transfer under fire conditions. This element is a 3-D layered shell element having in-plane and through-thickness thermal conduction capability. This element can be transformed into SHELL181, a four-noded element with six degrees of freedom at each node: three translations and three rotations about the principle axes, which is suitable for modeling 3D thin-plated structures. Such transformation is necessary to account for degradation in mechanical properties of CFS material at elevated temperatures as to accurately predict structural response of fire-exposed channel. The finite element model is meshed using equal side quadrilateral-type mesh to ensure uniformity. A typical FE model has an average of 9,000 elements. An isometric view of the developed finite element model is shown in Fig. 4.



(a) Test setup boundary conditions

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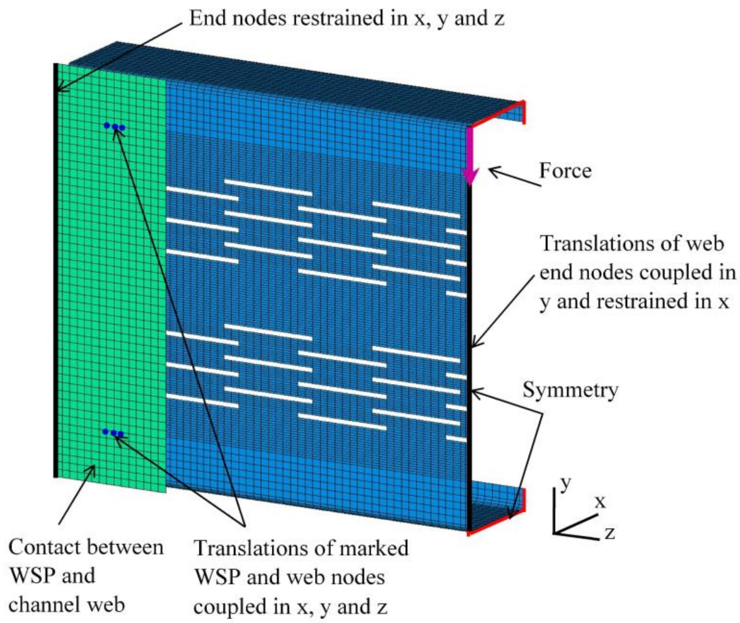

(b) Realistic boundary conditions

Fig. 4. Isometric view of finite element models (includes details to simulated boundary conditions, (a) test setup, and (b) and realistic)

In recent studies, Degtyarev and Degtyareva [10-13] reported that shear response of web slotted CFS channels can be sensitive to the type of applied boundary conditions. Hence, diligence was given to simulate boundary conditions and thus two different boundary conditions were considered in the study, simulating 1) the test setup, 2) realistic boundary conditions. In the first case, FE models representing slotted channels tested in three-point bending were idealized with test setup boundary conditions. However, in actual structures, typical support conditions of the CFS channels differ from those in laboratory tests and this was accounted for applying realistic boundary conditions [11].

Due to the symmetry of channels, arising from channels geometry, material properties and loading conditions, only one-half of each channel was modeled. This was ensured through proper application of symmetrical boundary conditions for both cases having test setup and realistic

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boundary conditions. In a typical FE model with test setup boundary conditions, two web side plates (WSPs) were added to the CFS channel such that one WSP was located at the far end support and another one located at the loading point (at mid-span of channel where symmetrical boundary conditions are applied). These WSPs were connected to the channel by coupling displacements of coinciding nodes in the plates and channel such that WSPs and web portion adjacent to the plates were restrained from translations in X-direction. Translational degrees of freedom in the node located in the middle of the bottom edge of the supporting WSP were also restrained in Y-direction. Further, vertical displacements of the nodes at the top edge of the WSP at the loading point were coupled. The load was applied to a pre-identified node with coupled vertical displacements.

On the other hand, the FE models with realistic boundary conditions had one WSP and this plate was located towards the end support (far from mid-span of channel). At the far edge, the nodes of this WSP were restrained from translations in all directions. The channel was connected to WSP by coupling displacements of nodes located in the plate and channel. In this case, standard contact was modeled between the channel and WSP. Displacements of the nodes at the near edge of channel were coupled in Y-direction and restrained in X-direction. The load was applied to one of the nodes with the coupled vertical displacements at the near channel edge.

4.2. High temperature material properties and constitutive laws

For undertaking fire resistance analysis, temperature-dependent thermal and mechanical properties of CFS material were input to the finite element model. Thermal properties include of density, specific heat and thermal conductivity, while, mechanical properties comprise of yield strength, Young's modulus, stress-strain relations and coefficient of thermal expansion. Both thermal and mechanical properties of CFS are assumed to vary with temperature as per Eurocode

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3 recommended relations [5]. The nonlinearity in cold-formed steel material was accounted for through a multilinear elasto-plastic constitutive material model based on the von Mises plasticity yielding criterion that accounts for large deformations. This material model is well-documented in Eurocode 3 [5] and is commonly applied in previous works [17, 19]. In this model, stress-strain curves are generated at specific temperatures (i.e. 100, 200°C..), at which appropriate degradation to mechanical properties (i.e. yield strength and stiffness) as well as associated strains is accounted for. It is worth noting that the ambient yield strength and modulus of elasticity of cold form steel was 500 MPa and 200 GPa, respectively.

4.3. Failure criteria

In the analysis, different limiting criteria namely flexural, shear and deflection limit states were considered for evaluating failure of the beam at each time step. Moment and shear capacity at a given time step were evaluated by extending room temperature design expressions to elevated temperature by replacing yield strength with that corresponding to the yield strength at specific temperature. Flexural or shear failure occur once the bending moment (or shear force) due to applied loading exceed the moment (or shear) capacity at a critical section. In addition, deflection limit state was also applied to evaluate failure at each time step. Accordingly, when the beam attains a deflection of ($L/400d$) or rate of deflection reaches ($L^2/9000d$); where L and d are the span and depth of the beam, respectively, the beam was said to fail [25]. Throughout the fire resistance analysis, a force convergence criteria of 0.005 tolerance was selected to minimize any numerical/solution instability arising from the complex nature of shear buckling.

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5.0 CALIBRATION OF NUMERICAL MODEL

Since there is a lack of published data on fire experiments of cold-formed steel beams with slotted webs, the developed finite element model was first validated against tests conducted at ambient conditions. These tests were carried out on channels with slotted webs in an earlier study [10]. Those channels had similar material properties, and geometric layout of the developed numerical model described above. The main outcome of the aforementioned experiments noted that CFS beams with slotted webs can experience 50% to 71% reduction in the ultimate shear strength; depending on the configuration of channel web slots.

While full details on these tests are spared for brevity and can be found elsewhere [10], still, for the sake of this work, one channel with slotted web is highlighted herein to show the validity of the developed model in predicting shear response of CFS channels at ambient conditions. This channel has nominal depth of 150 mm and nominal thickness of 0.9 mm. The web of this channel has two perforated regions and eight slot rows along web height. The distance between the perforated regions is 42 mm. The width of slots is 3 mm while their length was 75 mm. The slot rows are spaced at 9.5 mm on center.

A comparison between measured (experimentally observed) and numerically predicted load-deflection response history is plotted in Fig. 5(a). A closer look at shear force, *V*, and displacement history shows that there is a good agreement between measured and predicted response. In fact, the obtained mean difference between observed and numerically predicted results is reported at 0.93, together with coefficient of variation of 0.093. Figure 5(b) also shows comparison between failure mode shape of the tested channel and that predicted by the developed

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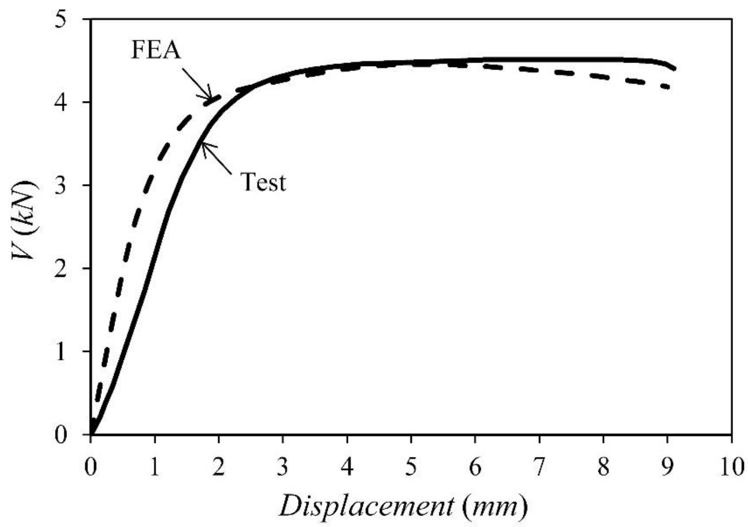
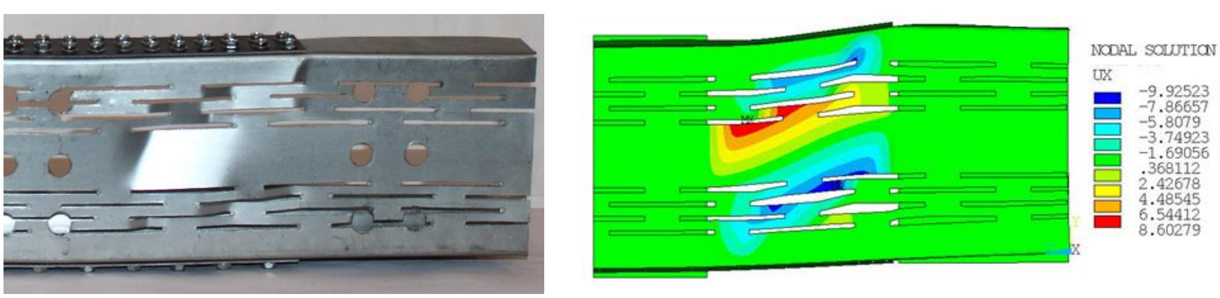
FE model. This comparison demonstrates that the FE model accurately captures the failure mode shape of the slotted channel. This shows that the developed model agrees well with measured shear strengths of slotted channels and is within acceptable accuracy from practical engineering point of view.



(a) Comparison between measured and predicted load-deflection response



(b) Failure mode shapes of tested specimen (left) and FE model (right)

Fig. 5. Comparison between test and FE simulation results of beam with slotted channel

In order to further calibrate the developed FE model, shear strength of all 36 CFS channels predicted from the FE numerical model are also compared against that calculated using design expressions such as those derived by Degtyarev and Degtyareva [10-13] and explicitly take into account presence of web slots. These equations consider three failure states in the web: shear yielding, inelastic shear buckling, and elastic shear buckling, and are given as:

$$V_n = V_y = 0.6F_y k_f A_w \text{ for } \frac{h}{tk_t} \leq \sqrt{\frac{Ek_v}{F_y k_f}} \text{ (Shear yielding)} \tag{1}$$

$$V_n = V_i = \frac{0.6\sqrt{EF_y k_f k_v}}{\frac{h}{tk_t}} A_w \text{ for } \sqrt{\frac{Ek_v}{F_y k_f}} < \frac{h}{tk_t} \leq 1.51\sqrt{\frac{Ek_v}{F_y k_f}} \text{ (Inelastic shear buckling)} \tag{2}$$

$$V_n = V_{cr} = \frac{\pi^2 E k_v}{12(1-\mu^2)\left(\frac{h}{tk_t}\right)^2} A_w = \frac{0.904Ek_v}{\left(\frac{h}{tk_t}\right)^2} A_w \text{ for } \frac{h}{tk_t} > 1.51\sqrt{\frac{Ek_v}{F_y k_f}} \text{ (Elastic shear buckling)} \tag{3}$$

where $A_w = ht$ is the gross area of the web element determined not accounting for the slots, k_v is the shear buckling coefficient of the whole channel section determined not accounting for the slots, k_f is the shear strength reduction coefficient due to the slots (accounts for the reduced area of the channel available to resist channel yielding or inelastic buckling), k_t is the web thickness modification coefficient due to the slots and the web stiffener. The tk_t expression can be considered as an equivalent (reduced) channel thickness to be incorporated into the above equations to take into consideration the reduced elastic buckling strength due to slots.

In addition, expressions initially developed by Pham and Hancock [14] for channels with solid webs, but numerically modified in a previous study [13], to account for presence of slots were also used in calibrating the developed FE model. These expressions are given as:

$$V_n = V_y \text{ for } \frac{h}{tk_t} \leq 0.697\sqrt{\frac{Ek_v}{F_y k_f}} \text{ (Shear yielding)} \tag{4}$$

$$V_n = \left[1 - 0.18\left(\frac{V_{cr}}{V_y}\right)^{0.27}\right]\left(\frac{V_{cr}}{V_y}\right)^{0.27} V_y \text{ for } \frac{h}{tk_t} > 0.697\sqrt{\frac{Ek_v}{F_y k_f}} \text{ (Shear buckling)} \tag{5}$$

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Similarly, the Keerthan and Mahendran [15] approach has been adjusted to the channels with slotted webs such that:

$$V_n = V_y \text{ for } \frac{h}{tk_t} \leq \sqrt{\frac{Ek_v}{F_y k_f}} \text{ (Shear yielding)} \quad (6)$$

$$V_n = V_i + k_{pb}(V_y - V_i) \text{ for } \sqrt{\frac{Ek_v}{F_y k_f}} < \frac{h}{tk_t} \leq 1.51\sqrt{\frac{Ek_v}{F_y k_f}} \text{ (Inelastic shear buckling)} \quad (7)$$

$$V_n = V_{cr} + k_{pb}(V_y - V_{cr}) \text{ for } \frac{h}{tk_t} > 1.51\sqrt{\frac{Ek_v}{F_y k_f}} \text{ (Elastic shear buckling)} \quad (8)$$

where k_{pb} is the post-buckling coefficient which can be assumed to be 0.4 but can also be determined through a rigorous procedure as shown in [13].

Table 2 lists shear strength (obtained from FE simulations) of numerically analyzed channels and compares numerical predictions to that calculated through the above listed expressions. It can be inferred from data listed in this table that the magnitude of numerically calculated shear strength is in close proximity in all cases, with slightly higher (conservative) variation when shear capacity was calculated using Eqs. 1-3 as these expressions do not account for additional increase in capacity provided by tension-field action (TFA). This shows the uniformity and good predictability of used design expressions for predicting shear strength of CFS channels. Table 2 also represents the equivalent state of channels at the failure (elastic buckling (EB), inelastic buckling (IB), or yielding (Y)) for each calculation method (i.e. used expressions). It can be seen that channels with stocky webs and with small perforations failed through inelastic buckling or yielding. Channels of depth of 150 mm and large perforations mostly failed through inelastic or elastic buckling (except 150-2-60-3-2-6-TS which failed in yielding). Finally, all

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slotted channels with slender webs and of 250 mm depth failed in elastic buckling (except 250-2-60-3-2-6-TS when shear strength was calculated using Eqs. 6-8)[§].

[§] It should be noted that three thicknesses (of 1, 2, and 3 mm) were selected for 150 and 250 mm deep channels with the aim of examining shear buckling of these channels. In majority of cases, channels of 150 mm depth failed before buckling and these channels were not further investigated. Only those which buckled before failure are presented and studied as they fit the scope of this study.

Table 2 Shear capacity and failure modes in CFS slotted channels

Channel	**Shear capacity (N)**				**Design equations/FEA**			**Types of failure**		
	FEA	**Expressions**						**Without TFA**	**With TFA**	
		Without TFA	**With TFA**							
		Eqs. (1-3)	**Eqs. (4, 5)**	**Eqs. (6-8)**	**Eqs. (1-3)**	**Eqs. (4, 5)**	**Eqs. (6, 8)**	**Eqs. (1-3)**	**Eqs. (4, 5)***	**Eqs. (6-8)**
150-2-60-3-1-6-TS	26951	24753	24187	24753	0.92	0.90	0.92	IB	B	IB
150-2-60-3-2-6-TS	25311	20877	21063	20877	0.82	0.83	0.82	Y	B	Y
150-2-60-3-1-6-R	30179	29814	28906	31614	0.99	0.96	1.05	IB	B	IB
150-2-60-3-2-6-R	27767	26601	24116	26886	0.96	0.87	0.97	IB	B	IB
150-2-60-3-1-8-TS	23685	21623	20978	21623	0.91	0.89	0.91	IB	B	IB
150-2-60-3-1-8-R	26757	26574	25249	27762	0.99	0.94	1.04	IB	B	IB
150-2-90-7-1-6-TS	11846	11609	11692	12671	0.98	0.99	1.07	EB	B	EB
150-2-90-7-2-6-TS	10475	9975	9193	10198	0.95	0.88	0.97	IB	B	IB
150-2-90-7-1-6-R	16510	15055	15228	16488	0.91	0.92	1.00	IB	B	IB
150-2-90-7-2-6-R	12763	12690	11614	12910	0.99	0.91	1.01	IB	B	IB
150-2-90-7-1-8-TS	11028	9953	10133	10956	0.90	0.92	0.99	EB	B	EB
150-2-90-7-1-8-R	13641	13419	13304	14471	0.98	0.98	1.06	IB	B	IB
250-2-60-3-1-6-TS	41311	40733	42932	46106	0.99	1.04	1.12	EB	B	EB
250-2-60-3-2-6-TS	39118	37347	37445	40622	0.95	0.96	1.04	EB	B	IB
250-2-60-3-1-6-R	43709	25014	49580	46046	0.57	1.13	1.05	EB	B	EB
250-2-60-3-2-6-R	39056	25014	42275	40261	0.64	1.08	1.03	EB	B	EB
250-2-60-3-1-8-TS	38789	34922	37203	39880	0.90	0.96	1.03	EB	B	EB
250-2-60-3-2-8-TS	34991	31974	32379	35049	0.91	0.93	1.00	EB	B	EB
250-2-60-3-1-8-R	40363	23078	43369	40572	0.57	1.07	1.01	EB	B	EB
250-2-60-3-2-8-R	35275	23078	36644	35342	0.65	1.04	1.00	EB	B	EB

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250-2-60-3-1-12-TS	33202	28112	30402	32510	0.85	0.92	0.98	EB	B	EB
250-2-60-3-2-12-TS	29721	25686	26379	28471	0.86	0.89	0.96	EB	B	EB
250-2-60-3-1-12-R	33264	20601	35910	34005	0.62	1.08	1.02	EB	B	EB
250-2-60-3-2-12-R	28873	20601	29953	29489	0.71	1.04	1.02	EB	B	EB
250-2-90-7-1-6-TS	21760	11103	20397	19147	0.51	0.94	0.88	EB	B	EB
250-2-90-7-2-6-TS	17435	11103	16084	15849	0.64	0.92	0.91	EB	B	EB
250-2-90-7-1-6-R	26713	11742	26044	23905	0.44	0.97	0.89	EB	B	EB
250-2-90-7-2-6-R	21461	11742	20345	19287	0.55	0.95	0.90	EB	B	EB
250-2-90-7-1-8-TS	18981	9343	17666	16512	0.49	0.93	0.87	EB	B	EB
250-2-90-7-2-8-TS	14915	9343	13902	13608	0.63	0.93	0.91	EB	B	EB
250-2-90-7-1-8-R	23422	10833	22784	21017	0.46	0.97	0.90	EB	B	EB
250-2-90-7-2-8-R	18042	10833	17636	16920	0.60	0.98	0.94	EB	B	EB
250-2-90-7-1-12-TS	13925	7325	14426	13409	0.53	1.04	0.96	EB	B	EB
250-2-90-7-2-12-TS	10587	7325	11319	10982	0.69	1.07	1.04	EB	B	EB
250-2-90-7-1-12-R	17750	9671	18869	17560	0.54	1.06	0.99	EB	B	EB
250-2-90-7-2-12-R	12686	9671	14416	14106	0.76	1.14	1.11	EB	B	EB
min					0.44	0.83	0.82			
max					0.99	1.14	1.12			
avg					0.76	0.97	0.98			
cov					0.247	0.079	0.071			

*Eqs. 4 and 5 only identify failure through yielding (Y) or buckling (B)

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As discussed above, there is limited work that examines the fire response of cold-formed steel beams with slotted webs. Due to the availability of actual test data on channels which were previously examined at ambient conditions by the second author [10], a decision has been made to utilize observations and measured data from those tests as a benchmark to predict fire response of cold-formed steel beams with slotted webs. This prediction would entail carrying out a coupled thermal-stress analysis by accounting for temperature-dependent thermal and mechanical material properties of cold form steel, appropriate element types, as well as various failure limit states as described in Sec. 4.0. This procedure has been adopted in a number of past and recent publications [17, 21], as well as practical case studies [26, 27], and is been shown to provide accurate prediction of fire response of structural members. More specifically, fire design codes (i.e. Eurocode 3) allow the use of advanced calculation procedure and as such, predictions obtained from the developed model can be used to showcase and investigate fire response of cold-form steel beams with slotted webs.

6.0 PARAMETRIC STUDIES

6.1. General

The above validated FE model is used to study the effect of shear parameters dominating structural response of CFS beams with slotted webs. More specifically, parameters associated with channel depth, web perforation pattern, and boundary conditions are studied (see Table 1). In each case, temperature at onset of buckling and at failure, as well as mode of failure where capacity of the fire-exposed CFS channel with slotted web falls below the level of applied loading, are compared between that obtained from finite element analysis with currently used methods.

6.2. Analysis procedure

While a common feature of all previously discussed methods such as those adopted in design codes [4, 5], as well as design expressions developed by researchers [10, 14, 15], is that they are tested for ambient conditions. These methods may still be extended for evaluating shear capacity of CFS channels with slotted webs under fire conditions by giving due consideration to temperature-induced degradation to yield strength and modulus properties of CFS at elevated temperatures [5][*]. Following this procedure, shear strength of CFS channels with slotted webs is first calculated using Eqs. 1-7 and then traced at elevated temperatures (i.e. 100, 200°C…). Failure in each channel occurs once shear strength falls below level of applied shear loading (estimated at 30% of shear strength at ambient conditions as listed in Table 2 and commonly accepted in the fire engineering community [25, 28]) – see Fig. 6. To maintain uniformity and minimize discrepancies between FE analysis and all applied methods, material property reduction factors for CFS is taken similar to that recommended by Eurocode 3.

[*] The validity of this rationale will be further examined in Sec. 6.3 upon analysis of results listed in Table 4.

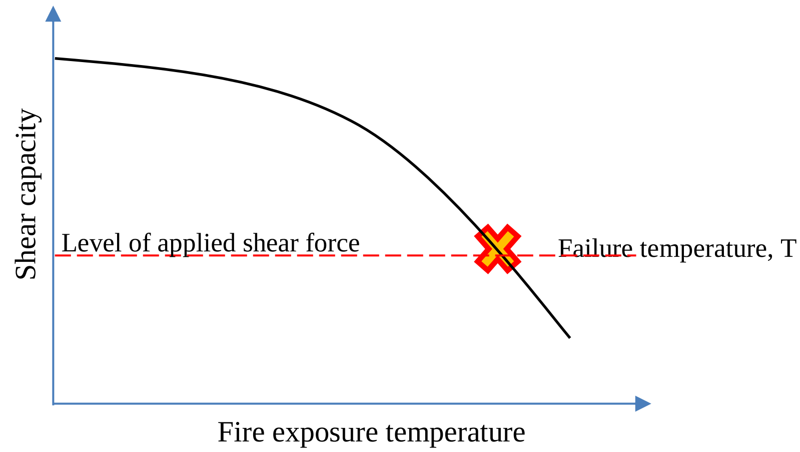

Fig. 6. Determination of failure in parametric studies

6.3. Discussion and results of parametric studies

Table 4 shows a comparison between temperatures at failure in slotted channels obtained from FE analysis, T_{FEA}, as well as different design expressions, T_{DE}. In general, failure of CFS channels with slotted webs occurs in temperature range of 625-660°C, with those of deeper sections, larger slots, and realistic boundary conditions failing towards the bottom side of this range, i.e. indicating higher susceptibility to shear failure. Analysis of data points listed in Table 4 also shows that there is a good agreement between numerically predicted and analytically obtained temperatures at failure of CFS slotted channels and this justifies and validate the rationale of extending design expressions (Eqs. 1-7) to elevated temperatures. Overall, the mean value of difference between temperature at failure as numerically predicted or obtained analytically, T_{DE}/T_{FEA} ratio, was 0.91 with higher ratios for slotted channels with deeper webs and larger perforations. The outcome of the carried out numerical analysis will further be elaborated on through discussion on figures tracing history and development of von Mises stresses at two particular points during fire exposure, i.e. onset of buckling, and towards failure of fire-exposed

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channels. This discussion on numerically obtained data is presented in each of the following sub-sections.

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Table 4 Temperatures at failure determined from FE analysis and design expressions for slotted channels

Channel	**Temperature at failure (from design equations), T_{DE} (˚C)**			**Temperature at failure (FEA), T_{FEA} (˚C)**			**T_{DE} / T_{FEA}**		
	Without TFA	**With TFA**		**Without TFA**	**With TFA**		**Without TFA**	**With TFA**	
	Eqs. (1-3)	**Eqs. (4, 5)**	**Eqs. (6-7)**	**Eqs. (1-3)**	**Eqs. (4, 5)**	**Eqs. (6-7)**	**Eqs. (1-3)**	**Eqs. (4, 5)**	**Eqs. (6-7)**
150-2-60-3-1-6-TS	670	660	670	657	660	657	1.02	1	1.02
150-2-60-3-2-6-TS	671	660	671	669	668	669	1	0.99	1
150-2-60-3-1-6-R	625	636	634	641	646	631	0.98	0.99	1
150-2-60-3-2-6-R	625	636	633	646	661	644	0.97	0.96	0.98
150-2-60-3-1-8-TS	668	660	669	659	663	659	1.01	1	1.02
150-2-60-3-1-8-R	625	636	634	641	649	635	0.98	0.98	1
150-2-90-7-1-6-TS	641	659	655	664	664	652	0.96	0.99	1
150-2-90-7-2-6-TS	642	659	655	658	668	654	0.98	0.99	1
150-2-90-7-1-6-R	625	636	634	667	665	654	0.94	0.96	0.97
150-2-90-7-2-6-R	625	636	633	654	666	652	0.96	0.95	0.97
150-2-90-7-1-8-TS	640	659	655	662	660	649	0.97	1	1.01
150-2-90-7-1-8-R	625	636	634	655	656	644	0.95	0.97	0.98
250-2-60-3-1-6-TS	630	658	651	633	625	618	1	1.05	1.05
250-2-60-3-2-6-TS	640	659	655	643	643	631	1	1.02	1.04
250-2-60-3-1-6-R	607	636	633	711	588	603	0.85	1.08	1.05
250-2-60-3-2-6-R	607	636	632	690	612	626	0.88	1.04	1.01
250-2-60-3-1-8-TS	628	658	650	650	641	630	0.97	1.03	1.03
250-2-60-3-2-8-TS	640	659	655	643	641	629	1	1.03	1.04

250-2-60-3-1-8-R	607	636	633	706	608	626	0.86	1.04	1.01
250-2-60-3-2-8-R	607	636	631	685	621	630	0.89	1.02	1
250-2-60-3-1-12-TS	624	658	649	658	647	638	0.95	1.02	1.02
250-2-60-3-2-12-TS	637	658	653	652	648	637	0.98	1.02	1.03
250-2-60-3-1-12-R	607	636	632	695	617	631	0.87	1.03	1
250-2-60-3-2-12-R	607	636	630	674	615	618	0.9	1.03	1.02
250-2-90-7-1-6-TS	611	658	654	736	652	661	0.83	1.01	0.99
250-2-90-7-2-6-TS	611	658	650	700	657	659	0.87	1	0.99
250-2-90-7-1-6-R	607	636	634	766	653	667	0.79	0.97	0.95
250-2-90-7-2-6-R	607	636	632	742	653	671	0.82	0.97	0.94
250-2-90-7-1-8-TS	611	658	654	741	652	661	0.82	1.01	0.99
250-2-90-7-2-8-TS	611	658	650	708	659	662	0.86	1	0.98
250-2-90-7-1-8-R	607	636	634	767	657	670	0.79	0.97	0.95
250-2-90-7-2-8-R	607	636	631	727	655	644	0.84	0.97	0.98
250-2-90-7-1-12-TS	611	658	655	738	640	651	0.83	1.03	1.01
250-2-90-7-2-12-TS	611	658	651	697	639	644	0.88	1.03	1.01
250-2-90-7-1-12-R	607	636	633	746	640	657	0.81	0.99	0.96
250-2-90-7-2-12-R	607	636	630	690	639	642	0.88	0.99	0.98
min							0.79	0.95	0.94
max							1.02	1.08	1.05
avg							0.91	1	1
cov							0.077	0.029	0.027

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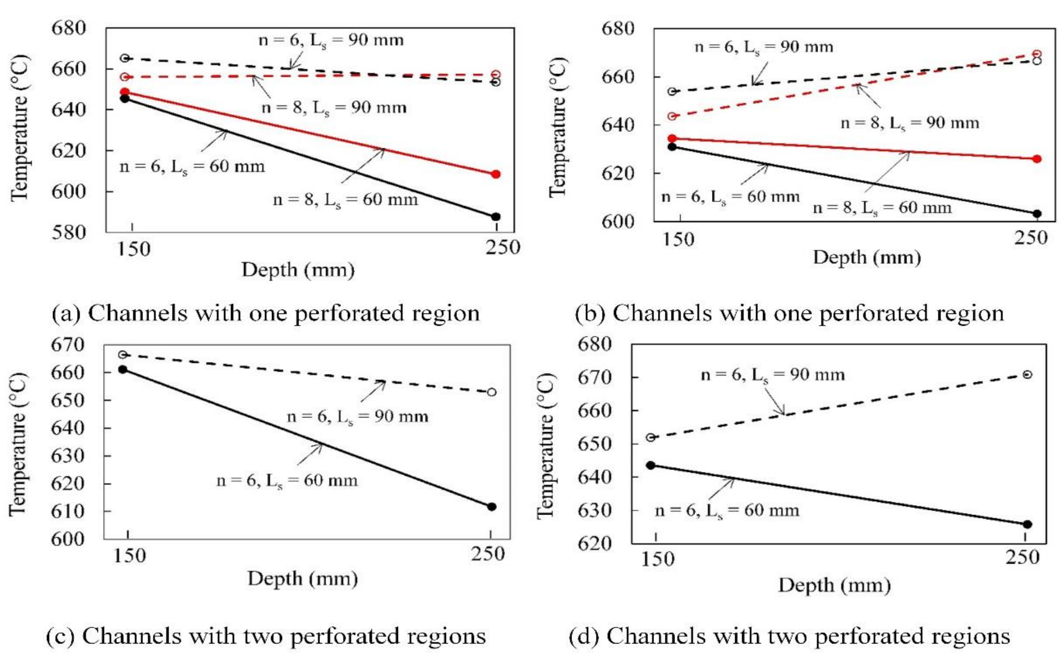
6.3.1. Effect of channel depth

As discussed in Sec. 4, two channel depths were selected for analysis; 150 mm and 250 mm. These depths are commonly used in practical building applications and hence deemed representative of cold-formed steel channels with slotted webs. Figure 7 shows the effect of varying channel depth on failure of slotted channels. This figure clearly shows that temperature at failure generally reduces when depth of channel (slenderness) increases for most considered perforation patterns (see Fig. 7). It is interesting to note that temperature at failure also reduces as the profile depth increases for channels with short and narrow perforations (L_s = 60 mm, B_{sl} = 3 mm) but seems to increase as the profile depth increases for channels with long and wide perforations (L_s = 90 mm, B_{sl} = 7 mm). This is due to the differences in ultimate shear capacities determined using different expressions and consequently to differences in applied loads as such loads were a percentage (30%) of corresponding shear capacity.



(a) Channels with one perforated region
(b) Channels with one perforated region
(c) Channels with two perforated regions
(d) Channels with two perforated regions

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Fig. 7. Effect of channel depth on temperature at failure in slotted channel models with realistic boundary conditions and with applied loads determined from Eqs. (4,5) (left) and Eqs. (6-8) (right)

Similar to observations made at ambient conditions, most slotted channel models with depth of 250 mm and 150 mm also failed in either elastic buckling or inelastic buckling under fire conditions. These channels were successfully able to develop post-buckling strength due to the tension field action, which can be seen in the von Mises contours of 150 and 250 mm deep channels in Figs. 8 and 9. These figures show that slender channels (of depth of 250 mm) buckled at much lower temperatures (and larger deformations) than stocky channels. This demonstrates the susceptibility of slender channels to shear loading and buckling. The same observation can be drawn when examining Fig. 9 (which illustrate stress and deformation state at failure of channels), however the difference in temperatures at failure was minor (of about 10°C). Some of slotted channels with realistic boundary conditions failed in a combination of shear buckling and web crippling (such as 250-2-60-3-1-6-R, 250-2-60-3-1-8-R, 250-2-60-3-1-12-R, 250-2-60-3-2-6-R, 250-2-60-3-2-8-R, 250-2-60-3-2-12-R as will be shown in Sec. 6.3.2).

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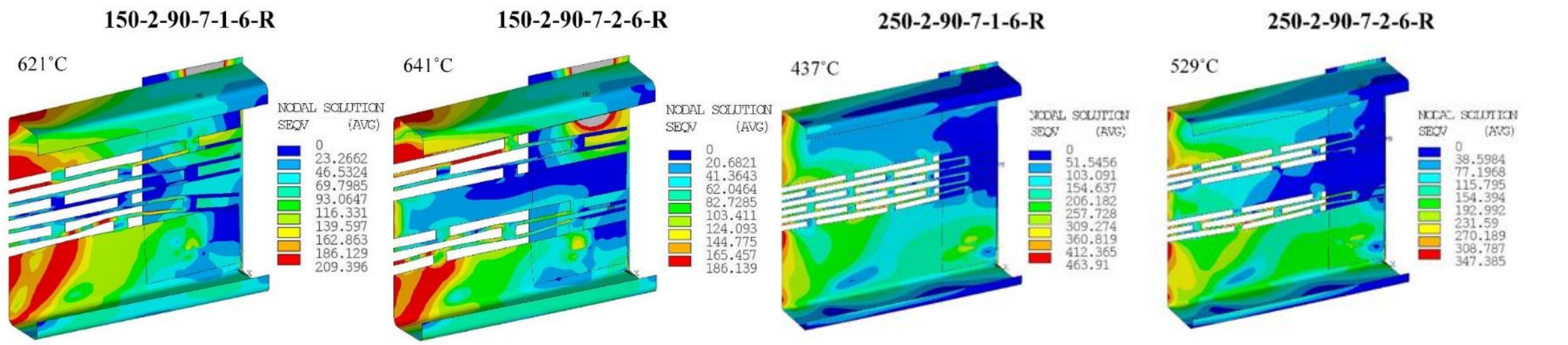
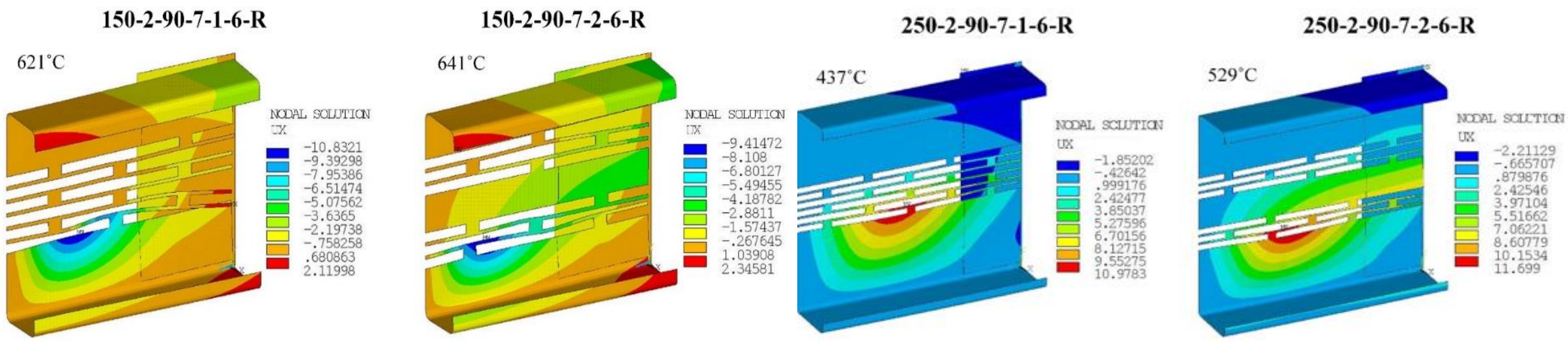


(a) Von Mises stresses in slotted channels



(b) Progression of failure in slotted channels

Fig. 8 State of channels with realistic boundary conditions (on set of buckling)

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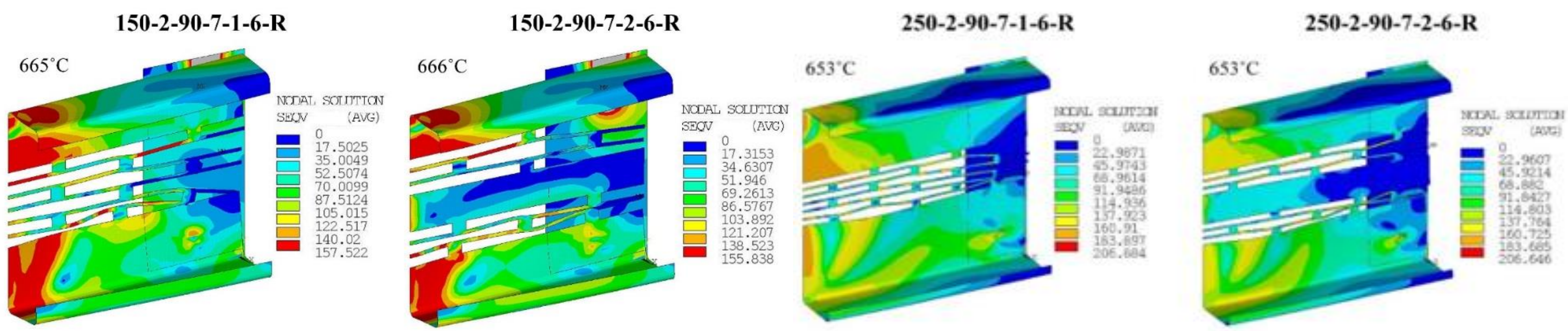
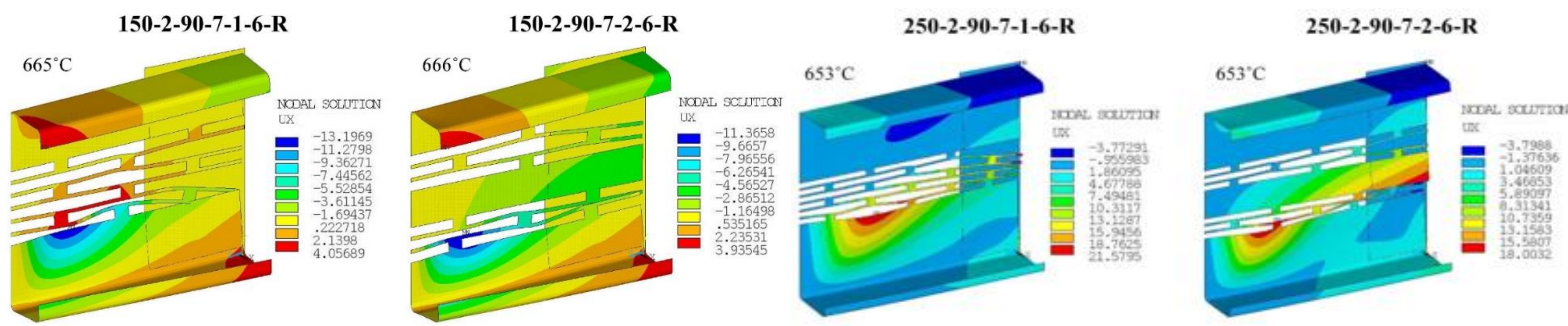


(a) Von Mises stresses in slotted channels



(a) Progression of failure in slotted channels

Fig. 9 State of channels with realistic boundary conditions (at failure)

6.3.2. Effect of web perforation pattern

In order to investigate the effect of perforation patterns on temperature at failure and failure modes of slotted channels, geometric features of web slots were varied. These parameters include slot length (L_s), slot height (B_{sl}), number of perforated regions (N) and number of slot rows across channel web (n). Predictions from FE simulations are plotted in Figs. 10-13 and these plots show how perforation pattern changes buckling mode of channels. The initiation of buckling and failure of channel was observed to occur at temperature range of 437°C-558°C and 588°C-657°C, respectively. This indicates that CFS channels with slotted webs can have an adequate fire performance significantly exceeding Eurocode 3 limit of 350°C and is also slightly lower than that reported by Liam and Rodrigues [21] for solid CFS beams ($T_{failure}$ = 700°C).

A common reflection among plotted figures show that having two perforated regions (for the same total number of slots) appears to delay occurrence of initial buckling by up to 70°C (in case of 250-2-90-7-1-8-R as compared to 250-2-90-7-2-8-R). This is unlike that observed in parametric studies at ambient conditions where the ultimate shear strength of the slotted channels with one perforated region were higher than those of the slotted channels with two perforated regions for all analyzed models [13]. This could be attributed to, 1) presence of a continuous and solid web in the mid-region of the channel which helps in carrying shear force and stiffens the channel under fire; and, 2) application of slightly lower loads as channels with two perforated regions had a smaller shear capacity. Further, in channels of 60 mm long slots, those with one perforated region buckled at relatively lower temperatures than those of two perforated regions. While both types of channels failed at relatively similar temperatures, few channels (i.e. 250-2-60-3-1-6-R and 250-2-60-3-2-6-R as well as 250-2-60-3-1-8-R and 250-2-60-3-2-8-R) failed at slightly different temperatures in the range of 13-24°C. It is worth noting that channels with larger slots buckle at lower temperatures than that of channels with smaller slots, the difference in failure temperatures can be as high as 60°C.

When it comes to examining failure mode of channels, Fig. 12 shows that all channels display deformation of about 10-15 mm at the onset of buckling. This deformation almost doubles for channels of small slots once degradation in strength reaches 50% that at ambient conditions. Channels with smaller slots fail in a combination of shear buckling within the shear span and web crippling at the supports. This causes large deformations to take in place in the transverse direction exceeding 29 mm in the case of 250-2-60-3-2-12-R. On the other hand, channels with larger slots appear to fail locally near the slots within the bottom of shear span. In general, channels fail once available yield strength reduces to about 0.38-0.56 of initial yield strength which corresponds to 190-284 MPa where channels with smaller slots achieving higher available strength values. Figure 13 also shows that despite failing at relatively lower temperatures, channels with smaller slots still failed at higher magnitude of von Mises stresses present in the web. This is unlike that shown in the case of channels with larger slots, where the right-side and middle portion of web seems to be ineffectively utilized in channels with one and two perforation regions, respectively.

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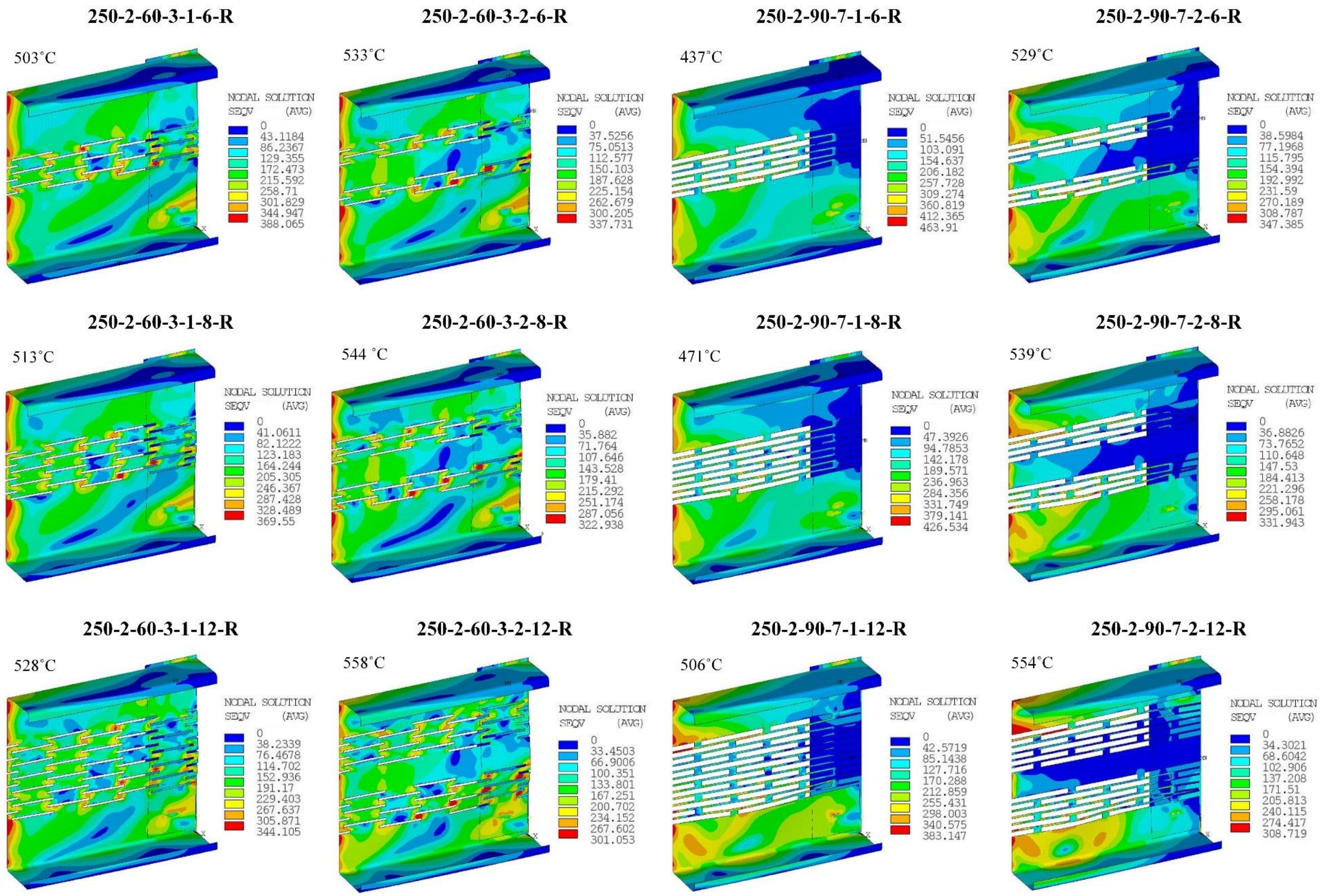

Fig. 10. Von Mises stresses in slotted channels with realistic boundary conditions (onset of buckling)

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Naser M.Z., Degtyareva N.V. (2019). "Temperature-induced Instability in Cold-formed Steel Beams with Slotted Webs Subject to Shear." Thin-Walled Structures. Vol. 136, pp. 333-352. (https://doi.org/10.1016/j.tws.2018.12.030).

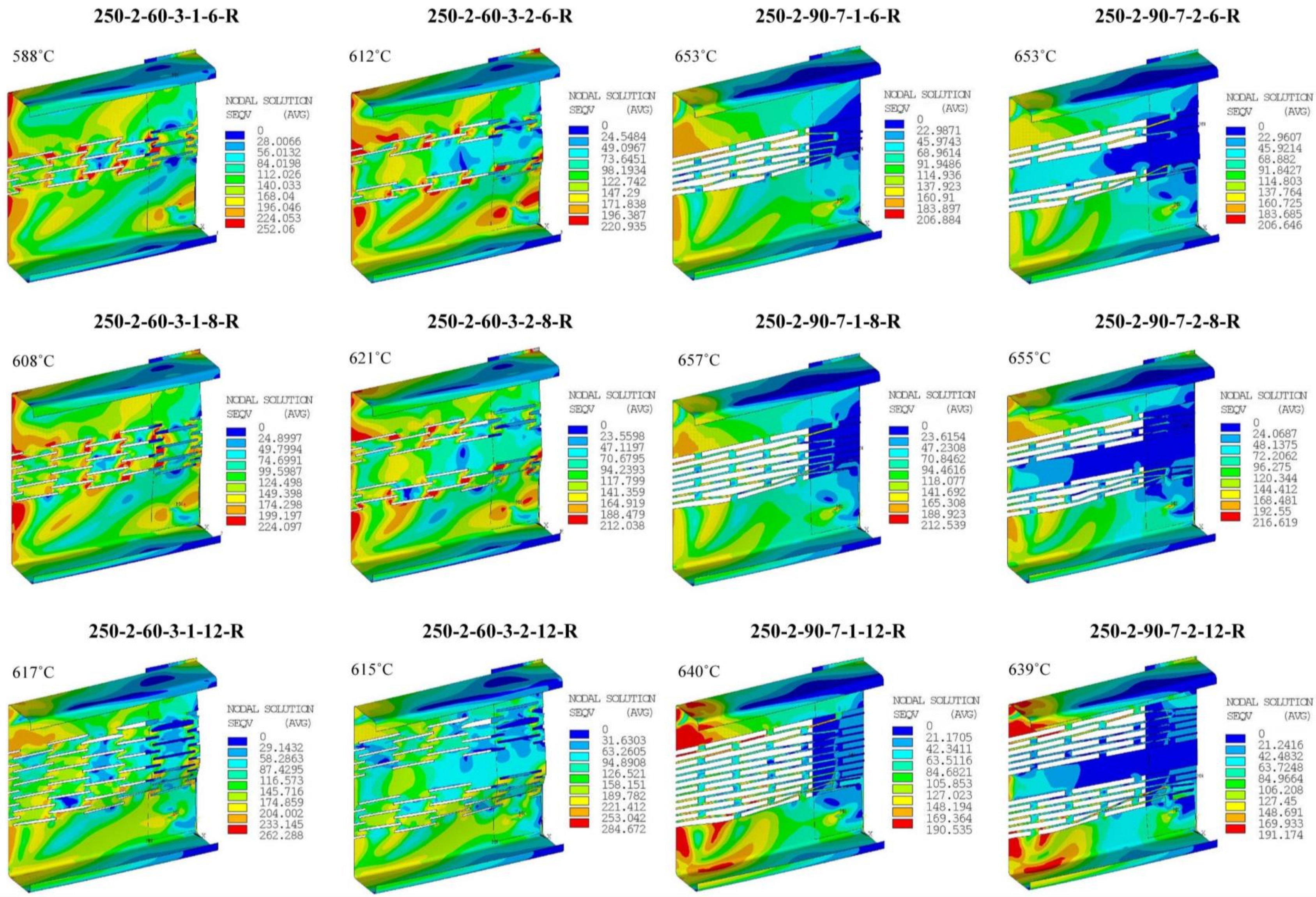

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Fig. 11. Von Mises stresses in slotted channels with realistic boundary conditions (at failure)

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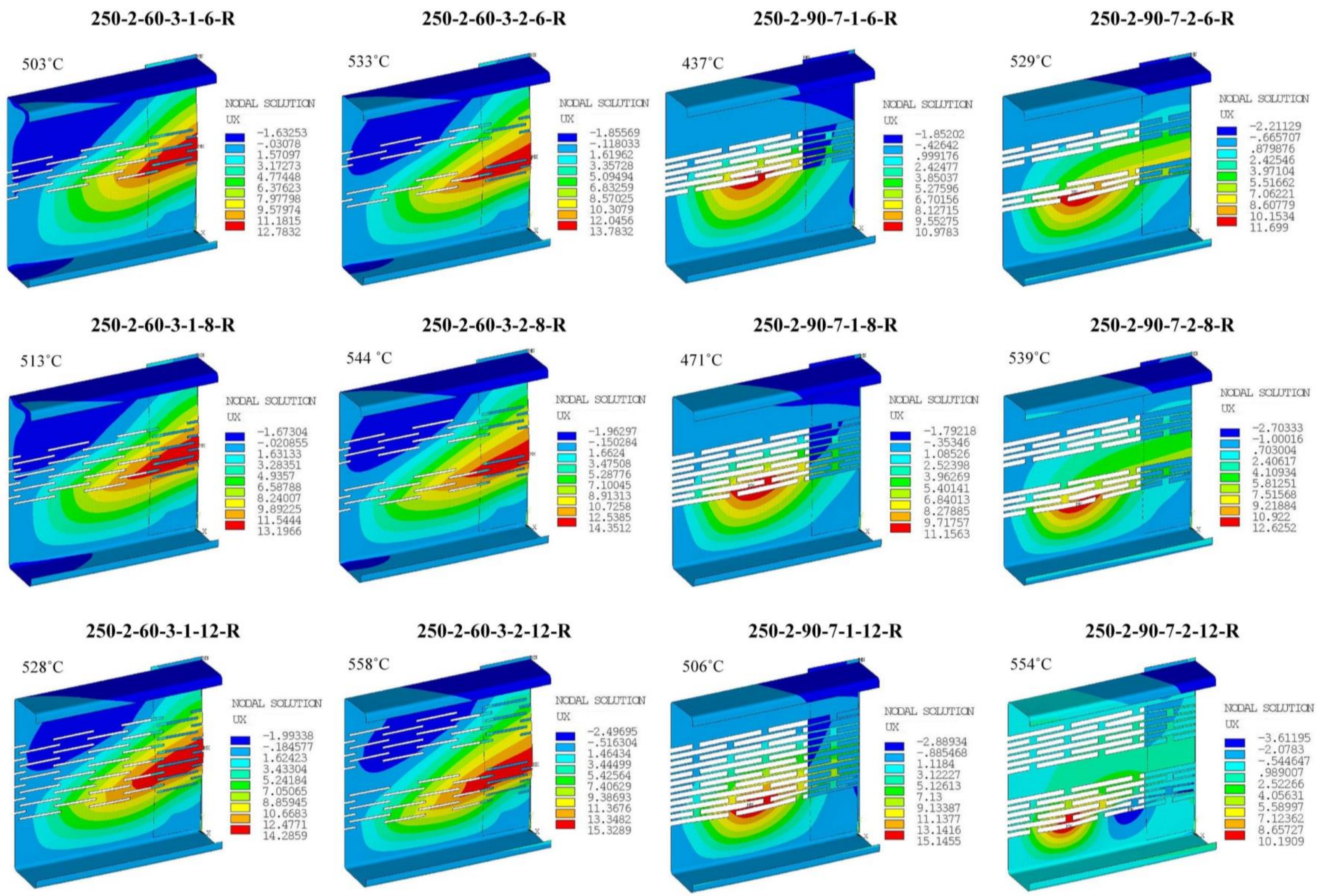

Fig. 12. Progression of failure in slotted channels with realistic boundary conditions (onset of buckling)

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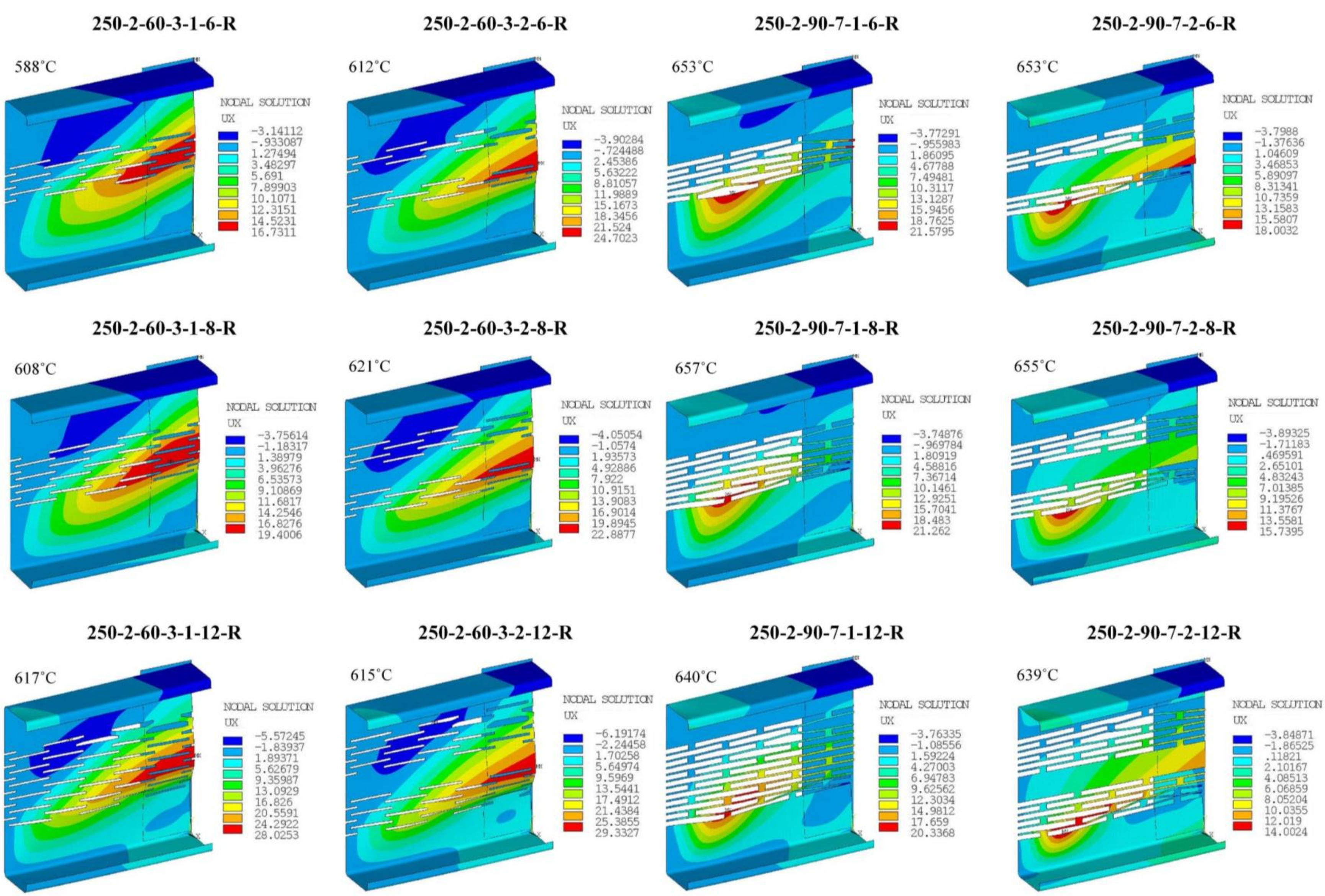

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Fig. 13. Failure of slotted channels with realistic boundary conditions

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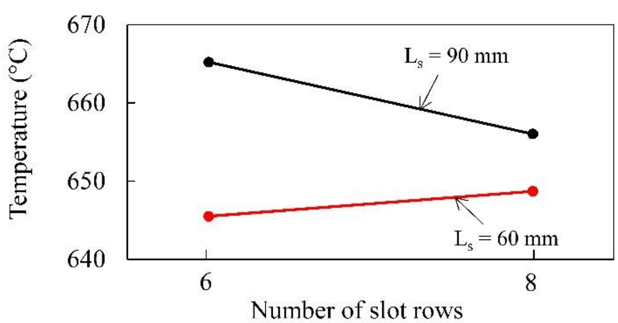
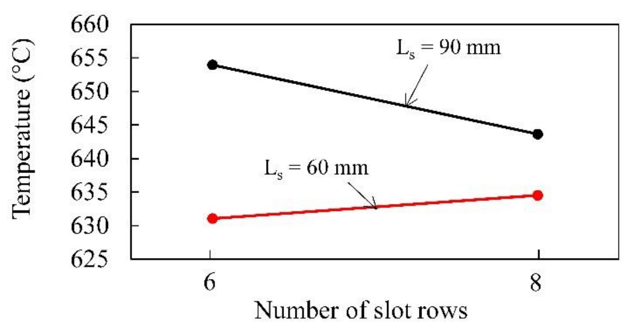
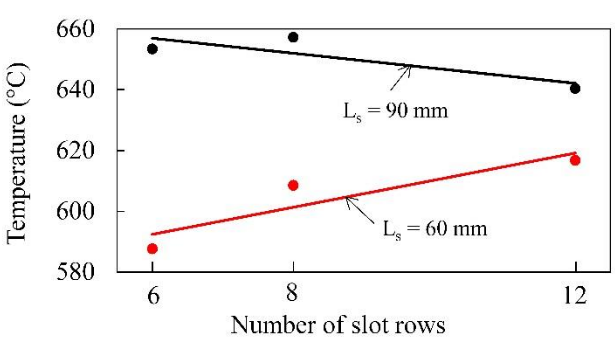
Key data observed from Figs. 10-13 are re-arranged into Fig. 14. This figure clearly shows that temperature at failure of slotted channels with one perforated region increases as the number of slot rows across channel web increases, especially in slots with smaller perforations (L_s = 60 mm, B_s = 3 mm), opposite to that in channels with larger slots (L_s = 90 mm, B_s = 7 mm). In channels with larger slots, the temperature at failure decreases as the number of slot rows across channel web increases. Moreover, in channels with two perforated regions, the effect of web perforation pattern on failure temperature seems to be minor (see Fig. 14d and e). Overall, the digression of temperature at failure were more noticeable for 250 mm deep channels as compared to that in channels with depth of 150 mm.



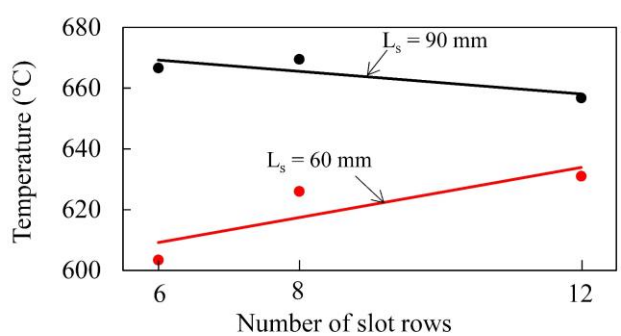
(a) 150 mm deep channels with one perforated region



(b) 150 mm deep channels with one perforated region



(c) 250 mm deep channels with one perforated region



(d) 250 mm deep channels with one perforated region

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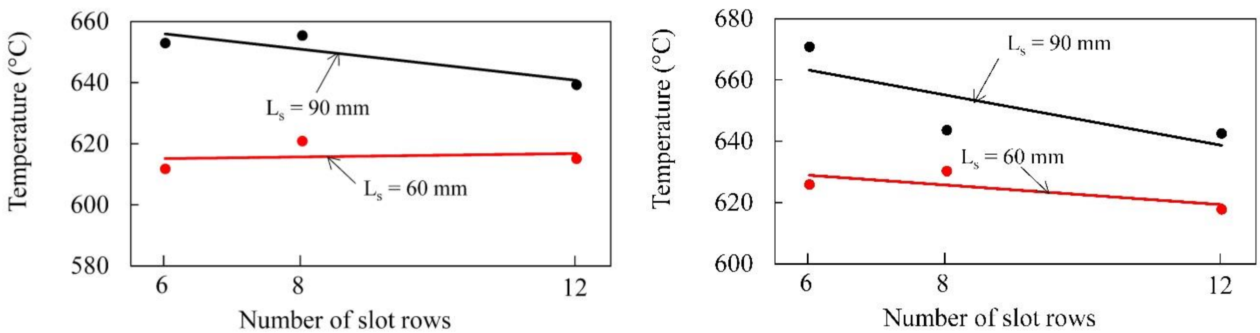

(d) 250 mm deep channels with two perforated regions

(e) 250 mm deep channels with two perforated regions

Fig. 14. Effect of number of slots in temperature at failure in slotted channel models with realistic boundary conditions and with applied loads determined from Eqs. (4,5) (left) and Eqs. (6-8) (right)

6.3.3. Effect of boundary conditions

Figure 15 as well as Fig. 13 examine the effect of restraint conditions on the shear response of CFS channels with slotted webs at onset of buckling. These figures show that applying idealized test-setup (TS) boundary conditions favors shear behavior of channels under fire conditions. For example, onset of buckling was positively delayed in all cases by an average ranging from 20-120°C. This delay was much apparent in channels with smaller slots, while channels with larger slots slightly benefited, if not at all. This was also observed at failure stage in channels, where channels restrained with TS boundaries, and with smaller slots, failed at relatively higher temperatures than that observed in channels with realistic boundary conditions.

It is interesting to report that when channels with larger slots are restraint with TS boundary conditions, these channels develop a more uniform stress distribution in between perforation regions facilitated by the symmetrical boundary conditions (see Figs. 15-18 as compared to Fig. 10-13). Another note is that using TS boundary conditions in channel 250-2-60-3-2-6-R stiffened the channel to only buckle once strength dropped to 50% of initial strength at ambient conditions. This can also be attributed to the additional restraints provided by the TS conditions; and that test setup boundary conditions result in higher shear buckling coefficients when compared with the realistic boundary conditions. Another observation to point out is that the magnitude of deformation on onset of buckling in channels with TS boundary conditions is much lower than that in channels with realistic boundaries, possibly due to the additional confinement provided by the WSPs.

A close examination of failure modes in cases where R and TS boundary conditions were applied shows that buckling in channels restrained with TS boundary conditions appear to be much more symmetrical than that in channels with R conditions. Further, buckling failure in TS-supported channels with small slots occurs towards the middle of the shear span as oppose to being towards the edge of the channel – please refer to Figs. 13 and 18. In addition, the degree of buckling in TS-restraint channels is less severe than those plotted in Fig. 13. In general, Fig. 16 shows that channels fail once available yield strength reduces to about 0.32-0.40 of initial yield strength which corresponds to 161-201 MPa where channels with smaller slots achieving higher available strength values.

Figures 17 and 18 also show that channels smaller with slots develop major stress concentrations at edges of slots which significantly damages the integrity of the web. On the other hand, channels with larger slots develop much larger stress concentration towards the top-most and bottom-most portions of the perforated regions which forces the web to globally buckle. Further, channels with larger slots and two perforation regions continue to under-utilize middle (solid) region of the web and this stress regions close to the upper and lower flanges. This observation was not shown in the case of corresponding channels with smaller slots and two perforations regions.

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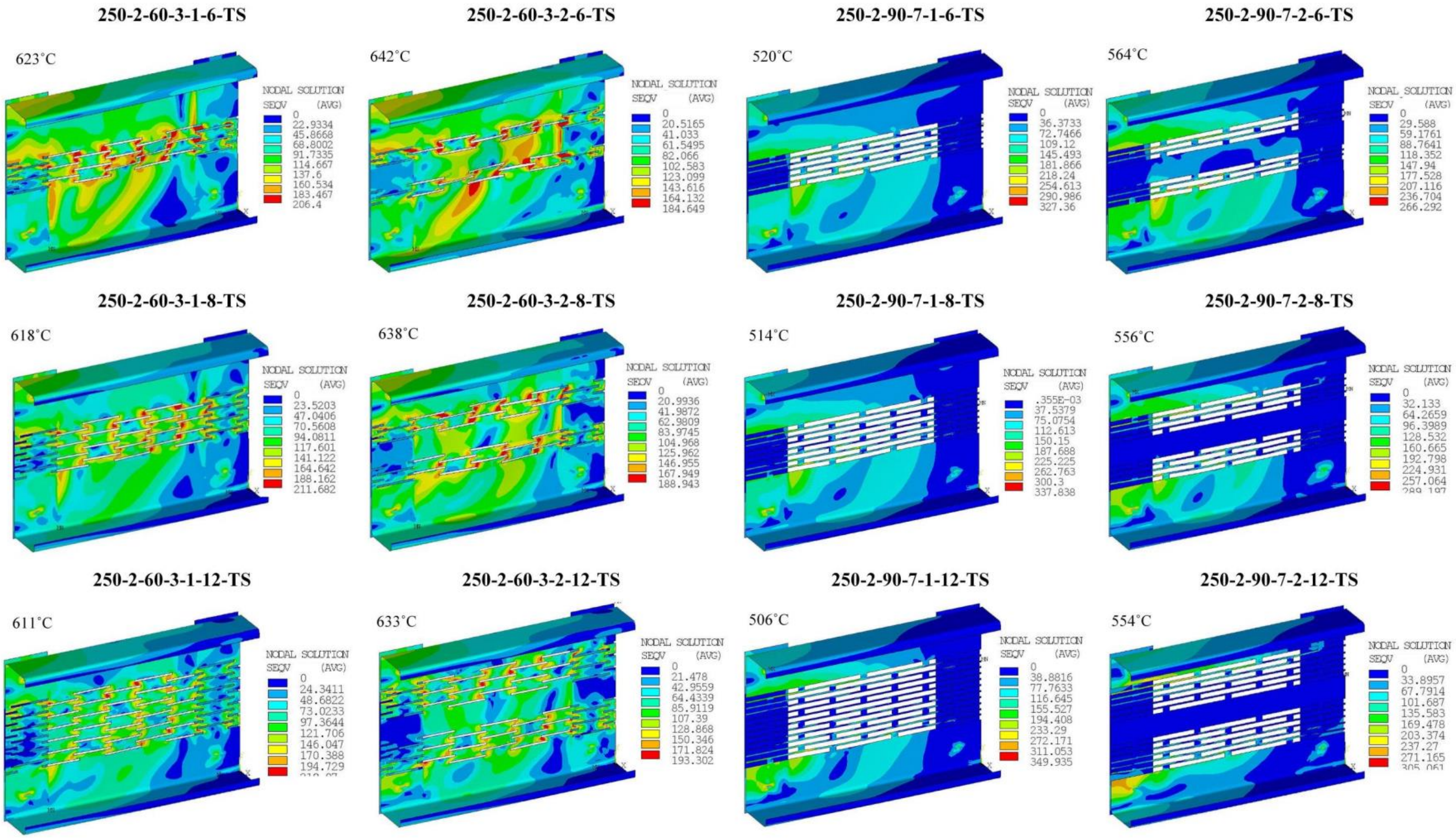

Fig. 15. Von Mises stresses in slotted channels with test setup boundary conditions (onset of buckling)

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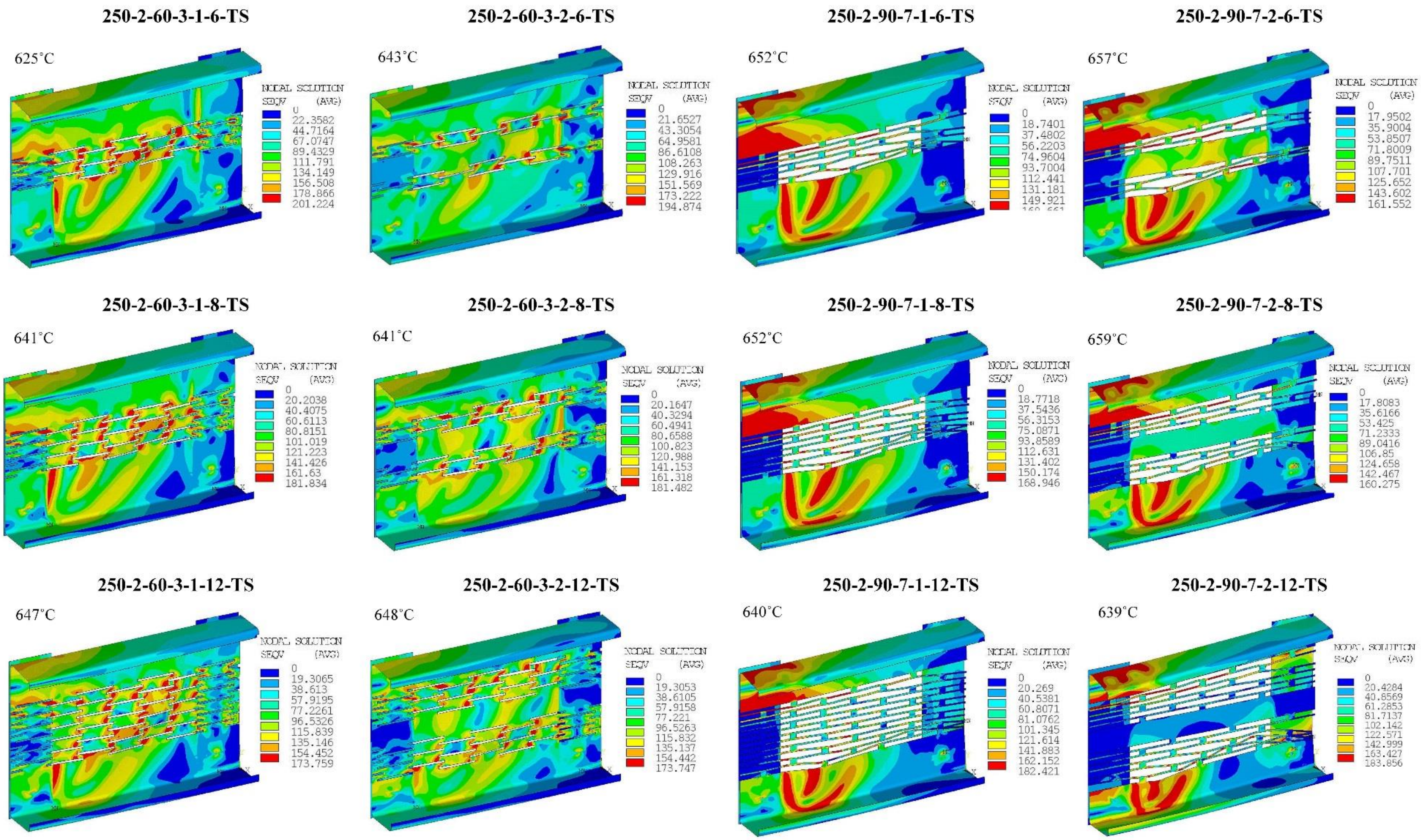

Fig. 16. Von Mises stresses in slotted channels with realistic boundary conditions (at failure)

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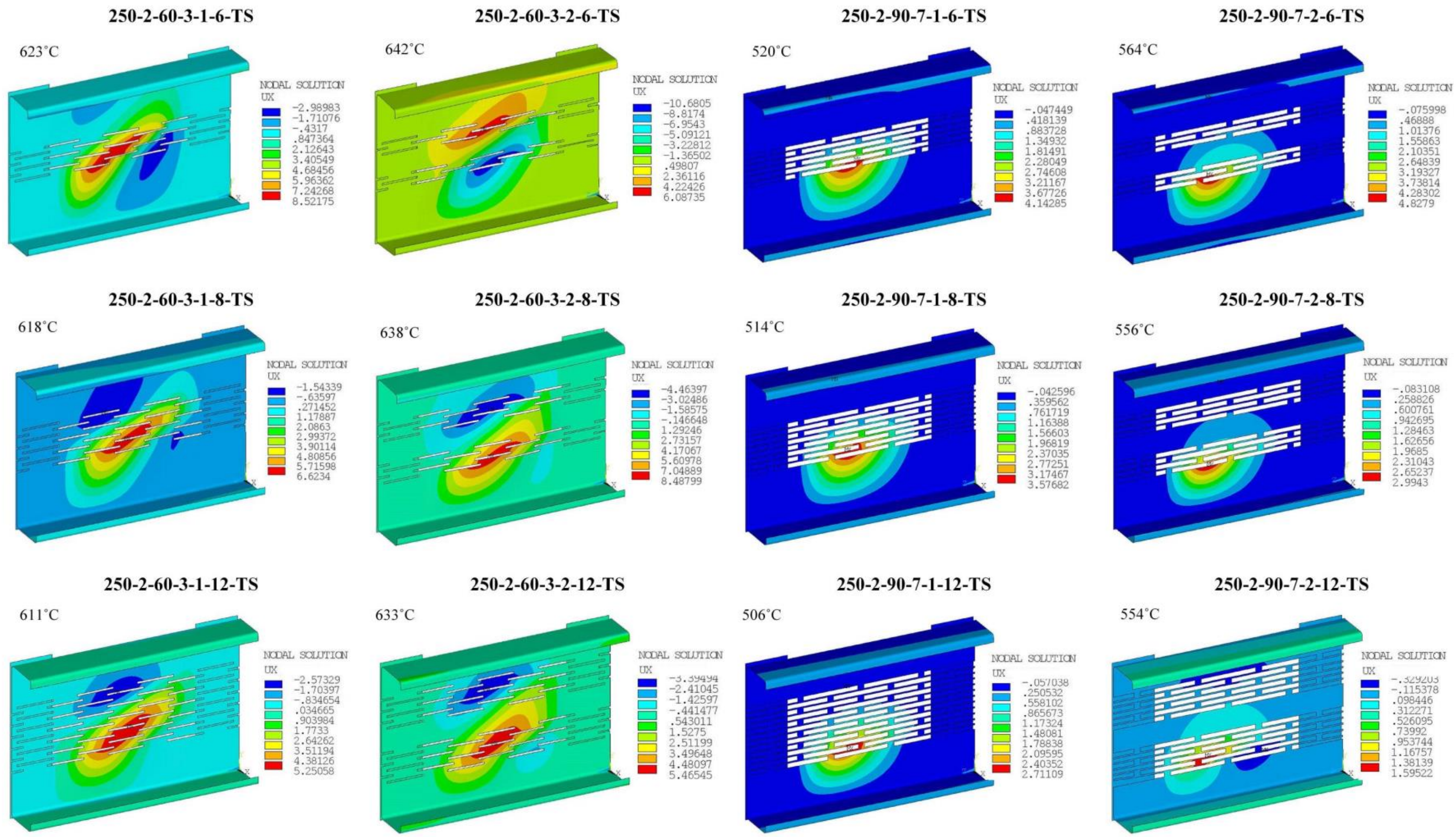

Fig. 17. Failure modes in slotted channels with realistic boundary conditions (onset of buckling)

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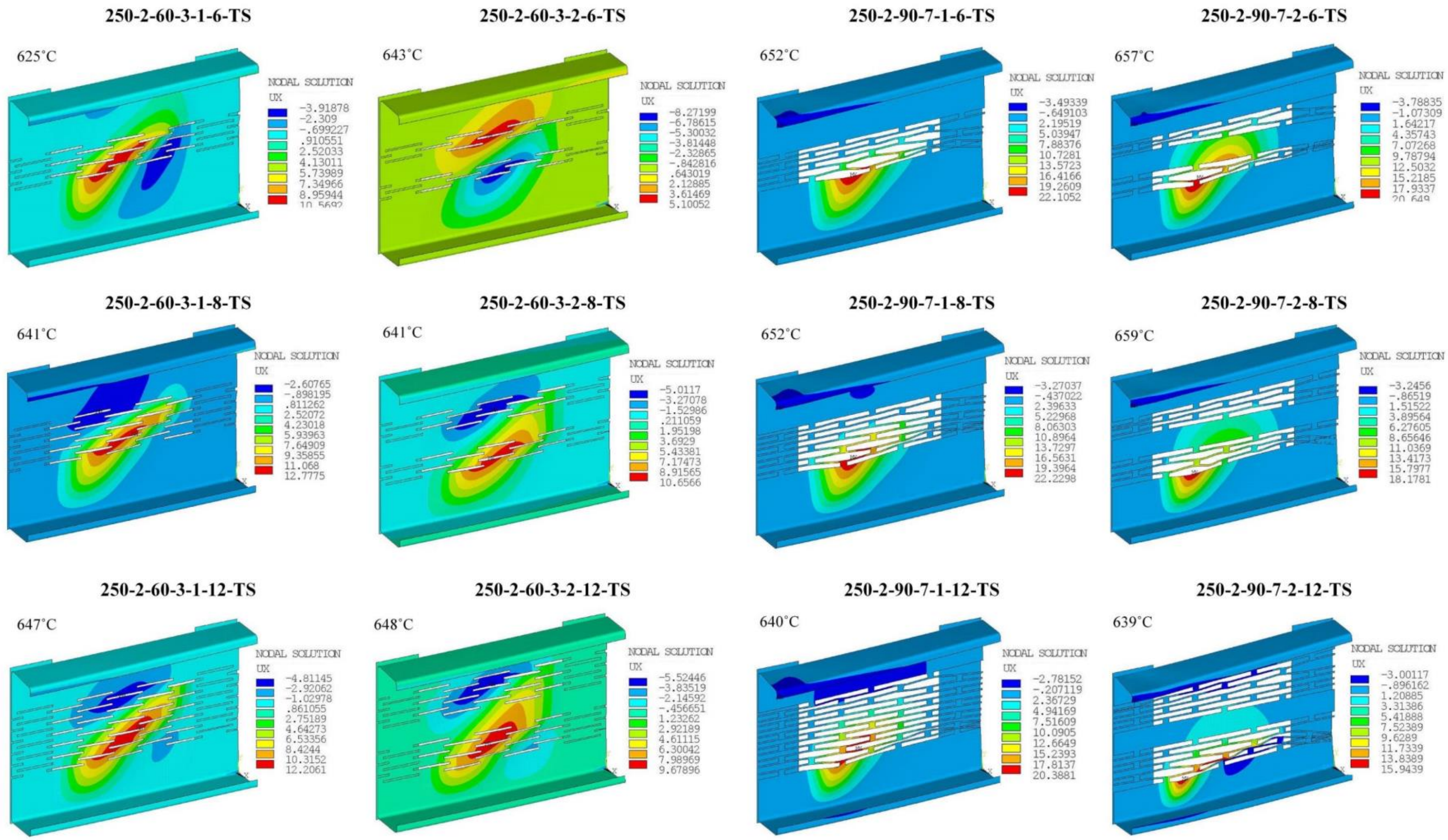

Fig. 18. Failure modes in slotted channels with realistic boundary conditions (at failure)

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Figures 19a and b show that channels with depth of 150 mm experience a unique behavior in which channels with smaller slots (with L_s = 60 or 90 mm and n = 6 or 8) fail at relatively lower temperatures when having realistic boundaries than when having TS restraints as compared to channels with larger slots. Only in one case, a channel (with L_s = 90 mm and n = 6) failed at slightly higher temperature, however, this variation in temperature is found to be very minor (of < 4°C). A similar but more apparent variation in temperature at failure was also witnessed in channels of 250 mm depth with L_s = 60 mm (see Figs. 19c and e). These figures show how temperature at failure point of slotted channels with test setup boundary conditions was higher than the temperature of the same channels but with realistic boundary conditions possibly due to the additional stiffness provided in TS setup. The effect of boundary conditions on fire response of 250 mm deep channels with one or two perforated regions with L_s = 90 mm seems to be negligible (see Fig. 19f).

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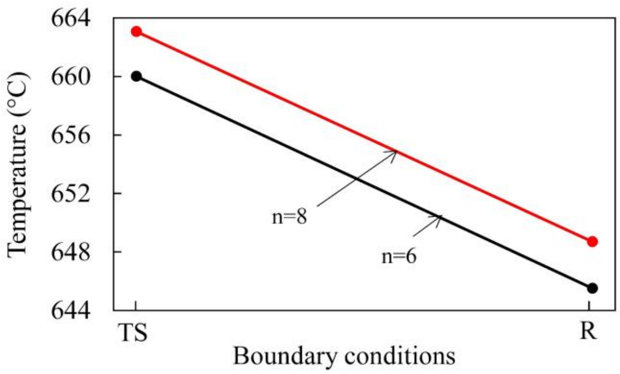
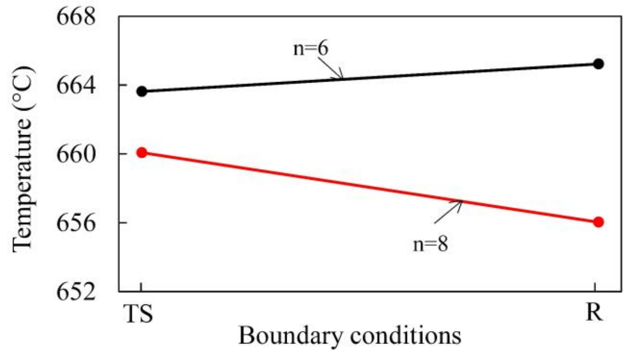
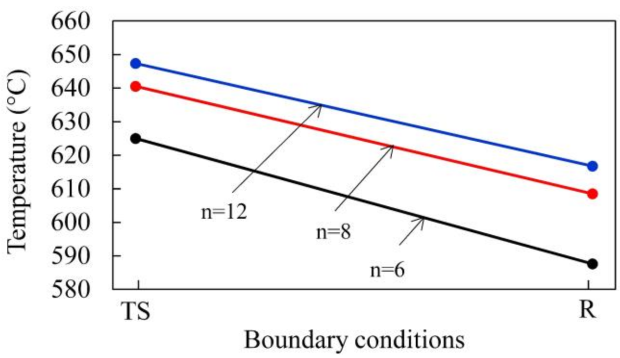


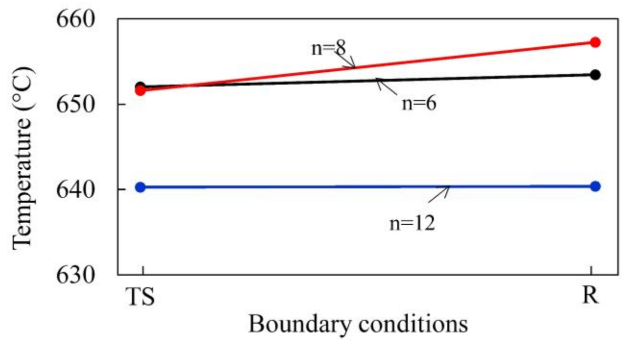
(a) 150 mm deep channels with one perforated region



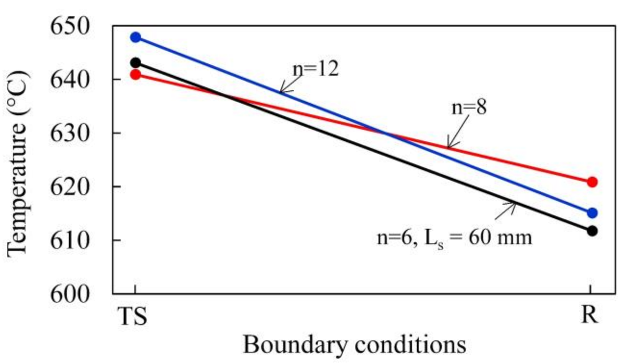
(b) 150 mm deep channels with one perforated region



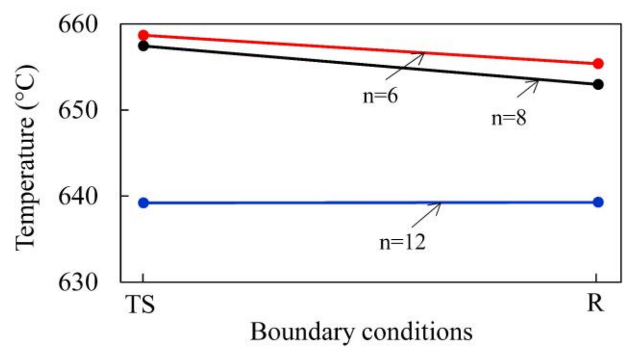
(c) 250 mm deep channels with one perforated region



(d) 250 mm deep channels with one perforated region



(e) 250 mm deep channels with two perforated regions



(f) 250 mm deep channels with two perforated regions

Fig. 19. Effect of boundary conditions on temperature at failure in slotted channels with L_s = 60 mm (left) and L_s = 90 mm (right) with applied loads determined from Eqs. (4,5)

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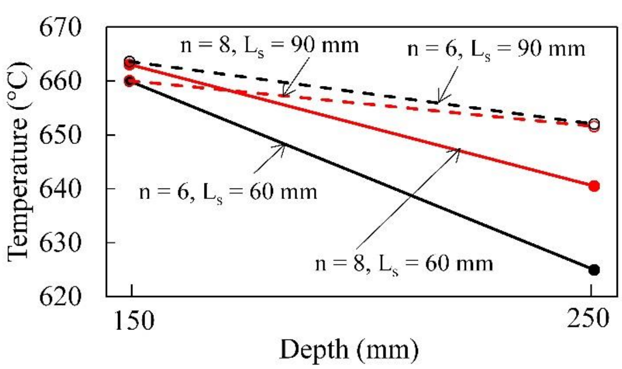
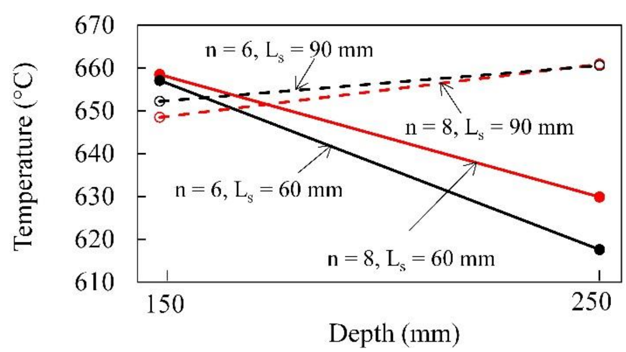
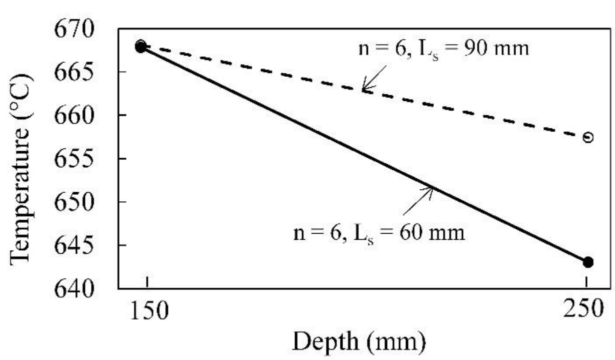
Figure 20 draws a comparison on effect of channel depth at temperature at failure of analyzed channels. As expected, failure of channels occurs at lower temperatures for slender channels (of 250 mm depth) as compared to that of stocky channels. In general, 250 mm deep channels fail at temperatures about 30-40°C lower than that of channels of 150 mm depth. Only in two cases, 250 mm deep channels of L_s = 90 mm and n = 6 and 8 actually failed at slightly higher temperatures (less than 10°C) than their corresponding channels of 150 mm deep. This behavior is deemed to be insignificant and it is then conservative to assume that temperature at failure in these channels to be same for both 150 and 250 mm depth.



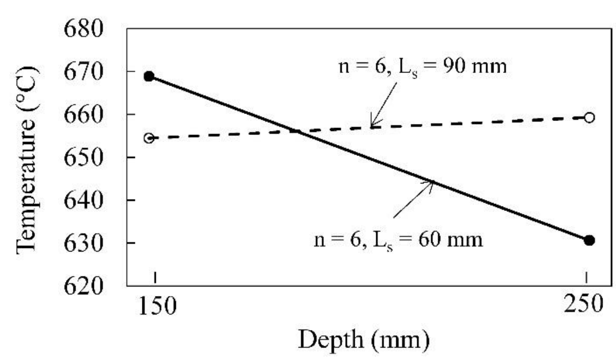
(a) Channels with one perforated region



(b) Channels with one perforated region



(c) Channels with two perforated regions



(d) Channels with two perforated regions

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Fig. 20. Effect of channel depth on temperature at failure in slotted channel models with test setup boundary conditions and with applied loads determined from Eqs. (4,5) (left) and Eqs. (6-8) (right)

Figure 21 also compares the effect of number of slots on temperature at failure of slotted channel models with test setup boundary conditions. This figure shows an interesting finding in which increasing the number of slots across the height of the web seems to be beneficial to fire resistance of CFS channels, given that slots are of L_s = 60 mm. This can be attributed to a combination of better thermal distribution of heat across the web and optimum reduction to web stiffness. Once size of slots increases to that of L_s =90 mm, this positive effect seems to reverse and channels with higher number of slots would fail at much lower temperatures.

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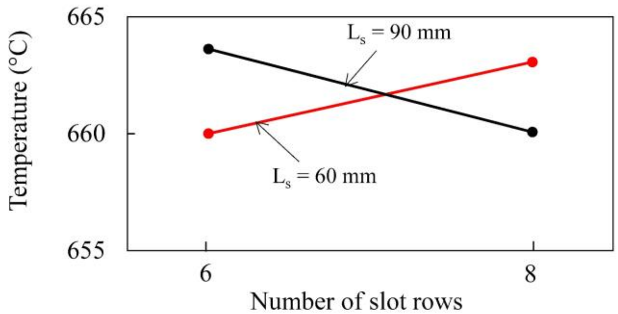
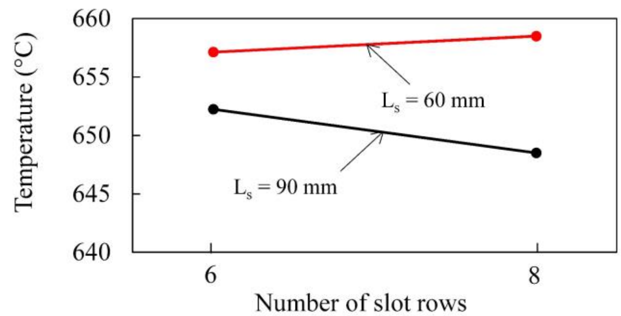
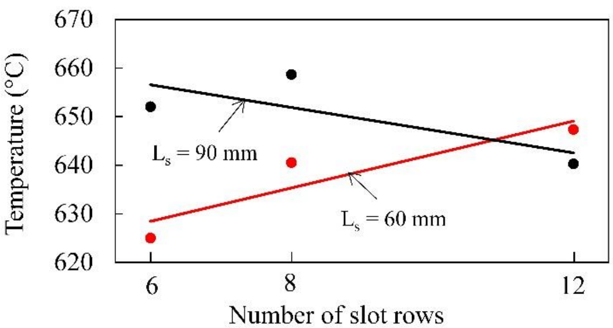


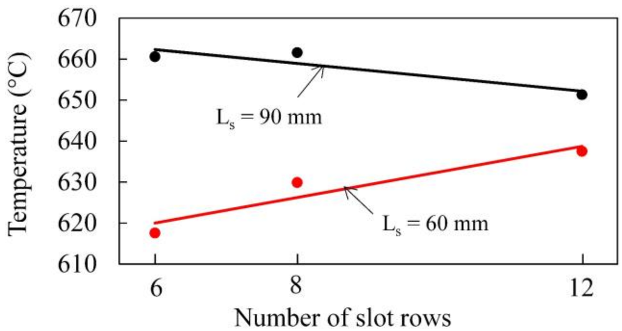
(a) 150 mm deep channels with one perforated region



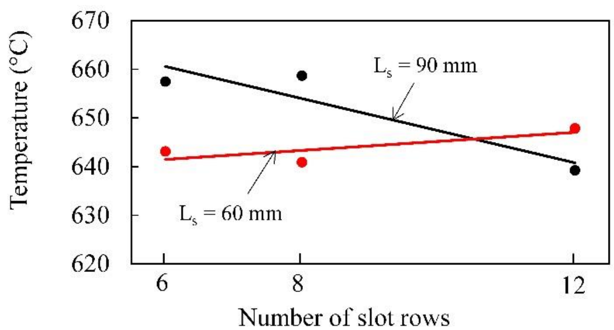
(b) 150 mm deep channels with one perforated region



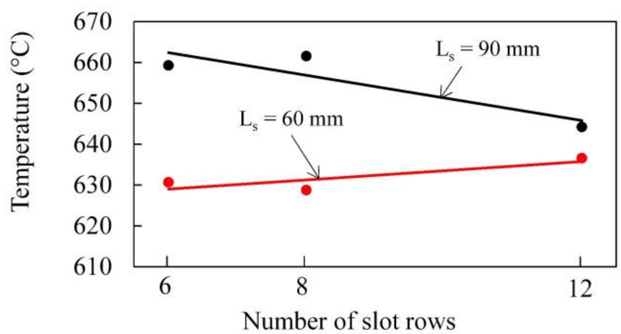
(a) 250 mm deep channels with one perforated region



(b) 250 mm deep channels with one perforated region



(a) 250 mm deep channels with two perforated regions



(b) 250 mm deep channels with two perforated regions

Fig. 21. Effect of number of slots on temperature at failure in slotted channel models with test setup boundary conditions and with applied loads determined from Eqs. (4,5) (left) and Eqs. (6-8) (right)

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7.0 Conflict(s) of interest

The authors declare no potential conflict(s) of interest with respect to the research, authorship, and/or publication of this article.

8.0 CONCLUSIONS

This study examines the response of CFS beams (of channel cross section) when loaded with shear loading under fire. It is hoped that outcome of this study, as well as that of related works [29-31], will help shed some light into the response of cold-formed steel beams with slotted webs under elevated temperatures, similar to that to occur in the case of a fire breakout. Through this understanding, the results presented herein will be utilized to set as a benchmark and then to specifically derive temperature-dependent design expressions that can accurately trace fire-induced shear buckling and response of cold-formed channels with slotted webs in a future work. Based on the results of the analysis presented herein, the following conclusions can be drawn:

1. CFS steel beams with slotted webs are sensitive to shear loading, especially under fire conditions. The outcome of this study shows that channel depth, web perforation pattern, and boundary conditions can significantly affect shear response of CFS channels as well as development of temperature-induced buckling susceptibility of CFS beams.

2. Analytically obtained (based on design expression) temperatures at failure are in a good agreement with finite element results. This implies that in order to accurately capture the response of fire-exposed CFS beams, an accurate presentation of geometric and material features in such members is essential.

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3. Unlike that observed in tests at ambient conditions, shear response of some slotted channels with two perforated regions can be higher than those of the slotted channels with one perforated regions.

4. Idealized boundary conditions favor shear behavior of slotted channels under fire conditions i.e. may delay onset of buckling temperature by an average ranging from 20-120°C. However, realizing such boundary conditions may not be realistic under fire conditions.

5. CFS channels with slotted webs can have an adequate fire performance significantly exceeding Eurocode 3 limit of 350°C. However, this performance remains slightly lower than that reported by other researchers who examined fire response of solid CFS beams.

6. It is recommended that future works carry out full scale fire tests on CFS beams with slotted webs in order to better understand the fire behavior of these elements as well as develop appropriate design approaches that can accurately capture the response of such beams.

9.0 NOTATIONS

A list of symbols used in this study is listed herein:

D	channel depth (mm)
t	channel thickness (mm)
L_s	slot length (mm
B_{sl}	slot height (mm)
N	number of perforated regions
n	number of rows of slots

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BC boundary conditions (*R*=realistic, *TS*=test setup)

A_w gross area of the web element determined not accounting for the slots

k_v shear buckling coefficient of the whole channel section determined not accounting for the slots

k_f shear strength reduction coefficient due to the slots

k_t web thickness modification coefficient due to the slots and the web stiffener

EB elastic buckling

IB inelastic buckling

Y Yielding of web

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