



Fire resistance of thin-walled cold-formed steel structures

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ABSTRACT

There is an increasing demand for cold-formed thin-walled steel structures on the building market nowadays. Owing to the assembly simplicity, materials' cheapness, high ecological standard, recycling, reuse potential, and other numerous advantages of such structures are widely employed in both office and residential buildings. The temperature of thin-walled structures increases rapidly as a consequence of the high section factor (measurement of the fire-exposed area to the heated volume), which creates the demand for a durable fire safety system, one of the fundamental requirements of the building safety. Although, several sufficient researches have been undertaken, there is still no strict performance-based fire design for cold-formed steel systems due to the lack of data. This paper compiles the existing works on the cold-formed thin-walled structures' fire performance, including numerical studies and experiments with mechanical and thermal properties of complete structures, purlins, joints (bolted, screwed, nailed, riveted etc.), plates, tubular structures, new calculation methods, new protective materials that are being used, such as intumescent coatings and etc.

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1. Introduction

Thin-walled cold-formed steel (CFS) structures have long been researched in numerous countries to prove their beneficial structural properties [1]. Being applicable in various ways and shapes, cold-formed thin-walled structures are of great demand on the construction market. With the increasing life-losses stated due to the inefficiency of fire safety systems buildings possess, it is crucial to develop proper methods and materials to enable structures withstand high temperatures. This particular article aims at accumulating existing studies and investigations in the area. The main objectives are as follows: to consider the fire performance of frame structures, wall systems as a whole, flexural and compression members and etc., following the chronology of experiments conducted; moreover, to observe the applicability of both traditional and modern fire-influence assessment methods and new measures of structural fire behavior enhancement, such as intumescent coatings.

Starting from 1990, some substantial studies on thin-walled frame structures have been undertaken in terms of fire resistance properties' enhancement. Prior to that studies, scientists explored the area, adding their comprehensive researches in store, including the studies of the behavior of cold-formed thin-walled steel structures at ambient and high temperatures. However, those works could be described as sporadic due to the lack of systematic approach, which is discussed and demonstrated in Norgaard's review [2].

Nonetheless, recently there have been advanced studies conducted on such structures, their components, materials and panels used together with thin-walled structures in commercial building industry, as experimental and analytical studies on cold-formed reticular-stretched profiles with the finite element method modeling [3], cold-formed sections' investigations [4, 5]. Almost all the significant factors and configurations defining the structures have been thoroughly analyzed, including buckling behavior and bearing capacity of C-shaped notched profiles [6–9], thin-walled cross-section's compression resistance and shear strength of their joints [10, 11], fatigue crack growth in a residual stress field experiments [12–14], initial imperfections effects [15–17], coupled instabilities [18, 19], the efficiency of partially closed cross-sections [4], sandwich panels' fastenings design methods and laser-stake welding [20–23], double skin panels made of cold-formed steel members [24], load-bearing capacity of structural parts and rod designs [25–30], and other works thoroughly described in various summary reports of the existing researches [31–35]. Cold-formed steel systems have become prominent in building construction as both load-bearing and non-load-bearing elements; thought the aim of the development of proper fire design has not been achieved yet [36, 37].

2. Frameworks and wall systems

Today CFS profiles' main application is in the construction of residential buildings, where they are used for construction of light steel framed (LSF) systems [38]. Assembled in different combinations, thin-walled structures are sensitive to elevated temperatures, blunting their stiffness and stability. Normally, LSF panels are exposed to fires from one side, causing non-uniform temperature distributions, leading to some complicated behaviors of such structural components as studs. The above-mentioned induces complex interactions with levels of plasterboard sheeting supports. Plasterboards are usually fixed on both sides of structural walls in terms of the studs' fire protection as it thwarts the temperature rise in the wall cavity until the entire board dehydration. Although the fire protection costs have been greatly lessened in reference to the new engineering decisions offered with the prospective studies, new engineering solutions are still required in recognition of economical inefficiency (as a result of exponential growth of demand for LSF structures) and what is more, the ability to withstand high temperatures of such structures mostly depends on steel members themselves but not on lining materials, which are intended to provide the lateral stability when the assemblies are exposed to fire [39].

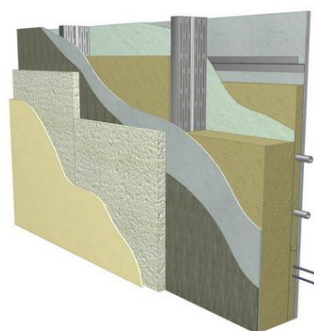


Figure 1. LSF panel

The studies on cold-formed thin-walled steel structures subjected to fire have long been basically based on the standard fire resistance test, which is not sufficient enough for managing a durable design for manufacturers. However, recently some research works have made a broad contribution to the issue, which is examined in the article.

Light Steel Framing systems are broadly used in the building industry nowadays [40]. Complete structures are vital to be tested for fire resistance to obtain the general fire-performance description as they basically provide structural support. Commonly, fire behavior of discussed structures is tested in accordance with Standard Test Methods and their equivalents: ASTM (developed in 2012), UL (2003), ISO 834 (1999).

Pil et al. [41] analyzed the fire safety of 3D frame structures such as industrial halls, having introduced the building with cold-formed thin plated elements used as structural components, which was submitted to a full-scale standard fire test.

At the same time, a lot of critics and disapprobation is now directed to the method supported by numerous facts. For instance, Grosshandler et al. [42] stressed that the environment of the furnace fails to mimic real fire and that the size of walls is also restricted by the furnace's limits.

That is why, questioning the applicability of standard fire testing to modern buildings originated from the application of wood furnaces. Mahendran et al. [43, 44] presented the detailed fire research into the performance of LSF walls, using real design fires based on developed Eurocode parametric curves and Barnett's BFD curves [45].

LSF walls have been long used cavity insulated to provide beneficial acoustics and climate control. Different types of insulations influenced the quality of thermal protection evinced. For example, cellulose and glass fibers, plasterboards can work as cavity insulation materials [46, 47].

Commonly, sheets of plasterboards are applied to delay fire expansions (Fig.1.). The optimal plasterboards' thickness determination is a common goal scientists target while working with cold-formed thin-walled steel structural panels. Feng et al. [48] presented the results of tests on the loaded steel panels sheathed with one layer of gypsum plasterboard on each side of the panel. As a result, the exposed plasterboard quickly lost its protective properties, whereas the unexposed one kept preventing structural buckling of steel channels.

Many scientists claim that in order to satisfy fire resistance requirements, usually R60, LSF systems should normally contain two layers of gypsum plasterboards on the side liable to fire. Analyzing load bearing wall assemblies lined with single or dual layers of plasterboards, Mahendran et al. [49] presented the results of wall models built and tested to study the thermal and structural performances. Kolarkar et al. [50] in turn investigated multiple panels (with more than 2 layers of plasterboards) and revealed that exploitation of such boards is beneficial, delaying the temperature rises.

Later Kolarkar [51, 52] developed a new LSF composite wall panel (Fig. 2.), where an insulation layer was used externally between the plasterboards on both sides of the wall frame instead of using it in the cavity. The panel preferences were given to the last type as procuring greater thermal protection. Moreover, Poologanathan's [46] fire tests based on design and Eurocode parametric fire curves proved the use of cavity insulation to be even detrimental to the walls' fire rating. Superior composite panel's performance was registered in Kolarkar's tests [50].

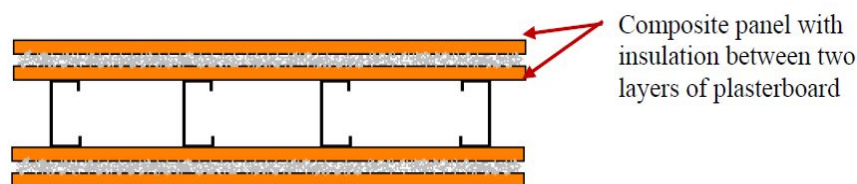


Figure 2. LSF composite wall panel with an insulation layer between the plasterboards

Kolarkar et al. [53, 54] also revealed that the external composite panel insulation of both load-bearing and non-load-bearing LSF walls enhanced the structural and thermal performances and increased their fire resistance rating. Furthermore, behaviors of both conventional and new composite panels were described in [55–57].

LSF walls made of welded hollow flange channel (HFC) sections lately became wide-spread. Its fire-resistance performance also needs to be studied. Kesawan et al. [58, 59] developed finite element models to predict the structural fire performance of LSF walls made of welded HFC section studs, trying to advance the use of HFC section studs.

Heinisuo et al. [60] investigated both statically determined and non-determined structures and revealed that whereas externally statically determined trusses are fairly accurately determined by the analysis, non-determined require corrections.

Tusnin et al. [61] performed numerical simulation to define the fire resistance of floor construction with the use of profiled sheeting.

3. Tensile tests

Ranawaka et al. [62] based a research project on experimental studies to investigate the deterioration of mechanical properties of light gauge cold-formed steels.

Intending to determine mechanical properties of certain steels, such as S280GD+Z steel with 2.5 mm thickness (used in cold-formed steel building construction industry), Craveiro et al. [63] assessed thermal properties using the Transient Plane Source (TPS) equipment.

Gunalan et al. [64] demonstrated a new set of equations to predict the post-fire mechanical properties of cold-formed steels in his study, also presenting the results of the cold-formed steel walls' evaluation.

Salminen et al. [65] presented the results of a finite element (FE) analysis of steel plates at non-uniform temperatures and proposed a design method for predicting the shear resistance of thin steel plate at non-uniform elevated temperatures.

4. Flexural members (beams)

CFS beams possess evident advantages due to high strength-to-weight ratio and flexibility of profiles and are thus increasingly used as load-bearing elements. However, in contrast to hot-rolled members, CFS ones are much more susceptible to instability failures (global and distortional buckling) even without temperature rises for their slenderness, flexural rigidity differences and low torsional stiffness. Since the variety of the profile shapes were designed, there is the need of systematic studies.



Figure 3. CFS profiles working as flexural elements (girders and purlins)

Accordingly, Laím et al. [66] presented the results of a wide-ranging experimental research carried on the flexural behavior of cold-formed steel beams (Fig. 3.) subjected to fire, evaluated the influences of the section geometry, the axial restraint to the thermal elongation of the beam and the rotational stiffness of the beam supports.

As LSF panels, CFS beams are often protected by plasterboards. Depending on how the member is protected, the temperature in a CFS member may be treated as time-dependent or both time- and position-dependent (when non-uniformly doused). Exploring the area, Cheng et al. [67] presented a numerical investigation on the buckling behavior of plasterboard protected CFS channel-section beams subjected to uniformly distributed loads when exposed to fire on its one side. Regarding a beam, it is important to consider restraints caused by adjacent structures, shear walls or vertical bracing, thwarting lateral forces. These interactions make beam behavior rather intricate. Santiago et al. [68] presented a numerical parametric study of a structural system consisting of an exposed steel beam restrained between a pair of fire protected steel columns.

Most wide-spread sections in CFS beams are lipped channel ones. Kankanamge et al. [69] gave a research for lateral-torsional buckling of cold-formed steel lipped channel beams at elevated temperatures, presented the details of the parametric study, comparisons with current design rules and proposed the new design rules.

5. Compression members (columns and studs)

Steel structures' behavior is vastly influenced by the buckling of steel members. High section factor (ratio of sectional area to volume) and thermal conductivity leads to the rapid heating of the members at elevated

temperatures, immensely deteriorating its stability. Apart from that, CFS columns are susceptible to local, distortional, flexural and flexural-torsional buckling effects and their interactions [70]. Hence, compression members (Fig.4.) exhibit complex structural behavior under fire conditions. Being poorly researched, the members demand reliable design rules.



Figure 4. CFS members used as pallet storage racks

Normally, steel members are protected by plasterboards or similar boards, subjecting studs or other components to non-uniform temperature conditions. However, there is a simple approach, allowing using a uniform elevated temperature design method in case the maximum temperature in the stud is estimated. Some research projects thus were based on experimental and numerical studies conducted at uniform temperature distributions by Ranawaka et al. [71] and Gunalan et al. [72] to investigate the distortional buckling behavior of CFS compression members under simulated fire conditions. Feng et al. [47], nevertheless, modified the ambient temperature design method for cold-formed thin-walled columns and included thermal-bowing effects of non-uniform elevated temperatures. Batista-Abreu et al. [73–75] also researched complex modal interactions in CFS columns (local-distortional, local-buckling and etc.) subjected to non-uniform conditions under thermal gradients.

Local buckling effects of steel columns exposed to fires are slightly provisioned in codes and standards. However, it is vital to consider. Wang et al. [76] examined the local stability of 12 steel stub columns at elevated temperatures under simultaneous application of load and fire conditions. The test variables included grade of steel, buckling resistance, temperature and load levels.

A localized fire is a fire which in a compartment is unlikely to reach flash-over and uniform temperature distribution. Designing for localized fires is generally more difficult than for flash-over compartment fires due to the complexity of the problem. Filling in the gap in experimental data, Byström et al. [77, 78] reported on a full-scale test series with a steel column exposed to localized fires.

Previously, Lee [79] investigated the local buckling behavior of unstiffened flange elements, stiffened web elements and stiffened web and flange elements at elevated temperature up to 800 °C. Incompatibility of the results gained and those proposed by the current rules lead him to put forward new design rules to predict the ultimate strength of cold-formed steel compression members subjected to local buckling events at elevated temperatures.

Thin-walled steel studs, being one of the main parts of wall systems, are vastly subjected to axial compression loads. Plasterboard linings, observed above, not only are fire-retarding but also restrain studs from deformations.

Traditionally, the effective width method that is based on calculating plates with same mechanical properties has been used in ambient temperature design. Nonetheless, having investigated wall studs, Shahbazian et al. [80, 81] stressed that with non-uniform temperature distributions mechanical properties are uneasy to assess with the effective width method and contraposed the Direct Strength Method (DSM), which

allows to work with complex channel shapes. Shahbazian also [82, 83] described new temperature calculation method where he used the weighted average of thermal resistances in the panel width direction.

Gunalan et al. [84], also driven by the absence of proper design rules for wall systems, embodying above all studs' complex structural behavior induced (thermal bowing, magnification effects, neutral axis shift and so on, presented the details of an investigation to develop suitable fire design rules for LSF wall studs under non-uniform elevated temperature distributions.

When estimating complex thermal structural parts' behavior it is desirable to use as many simplifications as possible. Commonly, the temperature distribution in the steel cross-section is assumed to be linear in the thickness direction and the average temperatures in the two flanges of the cross-section is used; also width direction heat transfer is neglected.

However, Shahbazian et al. [85] revealed the need to include the strong heat flow in a panel between the steel flanges and the adjacent materials into the steel section temperature calculation. He proposed a method of calculating the weighted average of thermal resistances, which helps to consider the effect described.

6. Joints

The type of joints applied in cold-formed structures (bolted, screwed, nailed, riveted, welded, adhesive) plays one of the dominant roles in fire performance of those [86]. Following works researched the area.

Lopes et al. [87, 88] as well as Heistermann [89] presented the results of the experimental investigation on a reverse channel component. The main focus was to characterize the behavior of steel joints between steel beams and tubular columns under natural fire loading and to assess the influence of different parameters on the behavior of the connection component at elevated temperatures.

Broadly used in racking systems, multi-storey and portal frames, bolted connections are regulated by design rules considering their ambient-temperature performances, which motivated following authors to investigate the applicability of these conservative design recommendations. Lim et al. [90] described non-linear elasto-plastic finite element parametric studies into the effects of elevated temperatures on bolted moment-connections between cold-formed steel members, proposing a simple reduction factor to the shear strength.

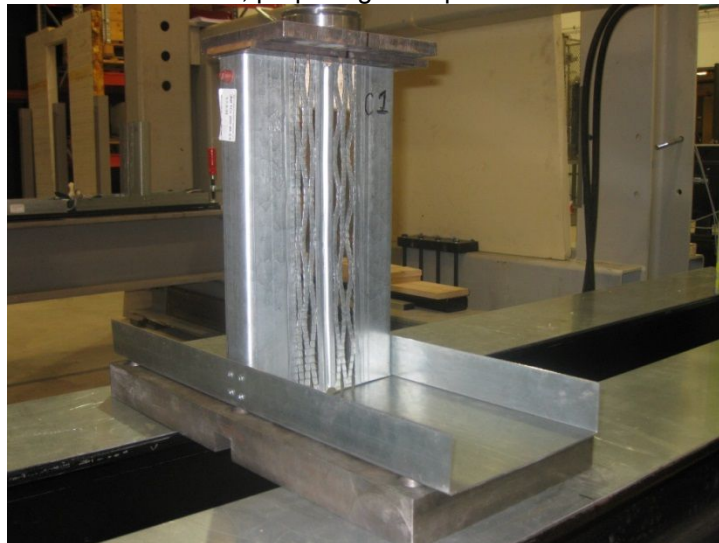


Figure 5. Screwed connection of CFS profiles

Young et al. [91, 92] conducted single shear bolted connection specimens (Fig.5.) and coupon specimens involving three different grades of stainless steel by using steady state test method. He, extending his previous research on the predictions of load-deflection characteristics of thin-walled bolted connections in shear at ambient temperature [93, 94], assessed the possibility to evaluate the connections with the same analytical methods under fire conditions [95].

Steel roof sheeting of cold-formed structures are commonly connected to a top truss chord through either nails or self-tapping screws. Complex behavior of steel sheeting (compressive to tensile forces transformation, catenary actions, deflections and so on) is in direct relation to its fasteners conduct. For instance, the protuberance feature has a significant positive contribution to the loading capacity of the joint, which was revealed in Lu's tests [96, 97]. Lu et al. [98] also numerically studied shot-nailed and screwed connections and provided design guidelines to predict the capacity of shot-nailed and screwed connections at elevated temperatures.

7. Intumescent coatings

Thin-walled sections demonstrate particular thermal conductivity. To delay temperature rise of steels exposed to fire intumescent coatings are applied. Owing to their advantages including: flexibility and ease of usage for both on- and offsite applications, light-weight, thin and attractive appearance, and high standard finish the coatings are becoming the dominant choice for passive fire protective materials.



Figure 6. Intumescent coating protection

Li et al. [99] investigated the feasibility of using a constant thermal conductivity for intumescent coating (Fig.6.) when calculating protected steel temperature in fire, based on analyzing a series of fire tests on intumescent coating protected steel sections with a range of section factors and intumescent coating thicknesses.

Gravit et al. [100, 101], trying to enhance fire-resistance properties of building structures, first examined, whether it's possible to estimate the pore space coating of intumescent coatings; she also improved the Russian Federation standard 55988-2014, having extended it with fire resistance tests' application.

Butler et al. [102] described the heat transfer and expansion processes within an experimental intumescent coating as a protective coating for structural steel.

Mohammadi et al. [103] studied the way hybride nano-particles (FGNP-TPP) affect the improvement of fire retardant properties of a traditional intumescent fire retardant (IFR) formulation for steel structures.

8. Conclusion

1. With the extension of thin-walled CFS structures on the building market the problem of structural fire safety have gained the common awareness, it can be followed that the number of fundamental researches on the topic has greatly exceeded. If in 2011 there were only few independent studies, now they are abundantly carried.

2. It has been shown in our analytical review that traditionally scientists apply FE and full-scale tests, studying fire performances of CFS structures, which is proved insufficient with the help of such methods as BFD and transient state tests.

3. Furthermore, observed studies stress ineffectiveness of conventional cavity insulation, instead, plasterboard insulation with multiple layers is propounded together with the superior composite Kolarkar's panel, procuring greater fire-resistance.

4. Fire-performance of flexural members' calculation is rather intricate for the restrictions adjacent structures impose, according to articles assumed in the review. This creates the need of systematic studies to fill in the gap in experimental data.

5. Susceptibility of compression members to different kinds of buckling effects and their interactions results in certain investigational complications, as proclaimed above. Due to the poor research base current rules lack precision, reflecting in the incompatibility of results gained in several studies included in the review. It all emphasizes the need of new profound studies.

6. Latest studies on intumescent coatings' application to thin-walled structures considered in the review demonstrated convincing feasibility of the approach. Nevertheless, it should be mentioned that there is also a lack of studies devoted to intumescent fire protection of the structures investigated, though, their applicability is shown to be promising.

7. It all inevitably leads to new calculation methods, simplified models, numerical approaches, equation sets and predictions are being proposed, which in its turn contributes to the development of the reliable design of cold-formed steel structures in fire, enabling building industry to thrive.

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Огнестойкость стальных тонкостенных конструкций

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АННОТАЦИЯ

Сегодня возрастает спрос на холодногнутые тонкостенные стальные конструкции на строительном рынке. Благодаря сборочной простоте, дешевизне материалов, высокой экологичности, возможности переработки и повторного использования и другим многочисленным преимуществам, такие конструкции широко применяются в строительстве как административных, так и жилых зданий. В случае возникновения пожара температура тонкостенных конструкций резко увеличивается из-за высокого соотношения площади, подверженной огню, к объему сечения, что создает потребность в обеспечении их огнестойкости. Несмотря на обилие исследований по данной теме, до сих пор нет четких требований по проектированию тонкостенных систем из-за недостатка экспериментальных результатов. Эта статья объединяет существующие исследования и эксперименты по исследованию механических и температурных свойств как целых сооружений, так и отдельно их частей: прогонов, балок, колонн, узловых соединений (болтовых, винтовых, клепаных и т.д.), плит, трубчатых конструкций. Статья также описывает новые методы расчета и новые защитные материалы, такие как огнезащитные вспучивающиеся покрытия и др.

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