DOI: https://doi.org/10.5592/CO/PhDSym.2021.05

Behaviour of thin-walled cold-formed steel structures in fire

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Abstract

Thin-walled cold-formed steel (CFS) members have become increasingly popular over the last decades in the light-steel frame (LSF) construction industry as primary load-bearing members. Valuable properties of CFS arise from the manufacturing process, while the undesirable ones, such as cross-section and member instabilities, are especially pronounced at extreme temperatures. Considering present-day stringent fire safety regulations, which require that all buildings and their structural components perform safely in fire situations, structural designers have to make greater efforts to understand complex structural behaviour at elevated temperatures. Besides laboratory testing, numerical analyses provide adequate and economic solutions for better understanding and predicting such complex behaviour.

Key words: cold-formed steel, fire design, laboratory testing, numerical simulation

Ponašanje tankostijenih hladno oblikovanih čeličnih konstrukcija u uvjetima požara

Sažetak

U proteklih nekoliko desetljeća, tankostijeni hladno oblikovani čelični elementi (CFS) sve češće se u lakim čeličnim okvirnim konstrukcijama (LSF) koriste kao primarni nosivi elementi. Vrijedna svojstva CFS-a proizlaze iz proizvodnog procesa, a nepoželjna svojstva, poput nestabilnosti poprečnog presjeka i elemenata, naročito su izražena pri ekstremnim temperaturama. S obzirom na današnje stroge propise u pogledu protupožarne sigurnosti, prema kojima sve građevine i njihove nosive komponente trebaju biti otporne na djelovanje požara, konstrukteri trebaju nastojati u što većoj mjeri proniknuti u složeno ponašanje konstrukcija pri visokim temperaturama. Uz laboratorijska ispitivanja, numeričke analize također pružaju prikladna i ekonomična rješenja koja omogućuju bolje razumijevanje i predviđanje takvog složenog ponašanja.

Ključne riječi: hladno oblikovani čelik, protupožarno projektiranje, laboratorijsko ispitivanje, numerička simulacija

1 Introduction

Ever since its introduction, cold-formed steel (CFS) has shown its advantages over traditional materials. The most important advantage is that steel is a non-combustible material and, due to low resistance of timber buildings to fire, CFS became interesting already in 1850 when it was for the first time applied in construction industry [1]. Over the past decades, CFS has been increasingly gaining in popularity in both industrial and residential constructions, and its members are widely used for load-bearing purposes in light-steel frame structures (LFS). For this reason, it is very important that structural engineers take into consideration load-bearing capacities at both ambient temperatures and at extreme temperatures during fire events [2].

CFS members exhibit a specific structural behaviour due to instabilities arising from the manufacturing process. Although such behaviour can be seen already at ambient temperatures, these members become even more sensitive in the case of extreme temperatures during fire events, because of non-uniform distribution of temperature through the cross-section. Usually, CFS members are a structural part of panel systems consisting of protection materials (e.g., pasteboard) and insulation materials (e.g., stone wool), which improve their thermal and structural performance. On the other hand, these materials result in less uniform temperatures. Thus, greater care must be taken to understand their complex structural and thermal behaviour.

The effective width method (EWM) is used in the traditional approach to structural design of CFS for ambient temperatures [3]. The new and currently growing replacement for this method is the Direct Strength Method (DSM), which combines local, distortional or global buckling, with cross-sectional resistance [2]. Both methods can be used in the fire design of CFS members, where DSM advantages are more pronounced. Because of the non-uniform distribution of temperature in CFS members, cross-sections must be divided into a large number of parts (strips) of uniform temperature, which will influence various mechanical properties of each part. This is why DSM seems to be a better approach in design, and could be preferred to the traditional EWM [2].

Design can also be carried out using a more sophisticated approach involving parametric numerical simulations with general FE software such as ABAQUS [4]. ABAQUS is applied for both heat transfer modelling and structural analysis. The structural-thermal analysis is performed so that realistic temperature profiles can be used in the simulation of structural response. This method is more exact than any hand calculation method but requires modelling experience, and it is always important to demonstrate simulation validity with experimental results.

Building with CFS is still in the development phase due to the lack of tests and studies. There are many studies on which Eurocode is based, but they are usually numerical without an experimental method that would enable comparison [5]. This is why every new experimental study with numerical simulation is one step forward toward better and simplified design, especially in the sphere of fire design.

2 Production of cold-formed steel frames

The name of cold-formed comes from the forming method used in the manufacturing process, during which steel remains in a cold state. Unlike the hot-rolled steel (HRS), the cold-formed steel is formed at roughly room temperature which makes it different in chemical composition, i.e., making it strong, durable and lightweight, among other valuable properties. Methods of forming CFS are cold roll forming, press brake operation, and bending brake operation. Roll forming, as the fastest manufacturing process, is usually used for building components such as individual structural members. Machine pair of rolls progressively form strips into the final required shape. The thickness of steel strip generally used in cold-formed steel structure members ranges from 0.38 mm to about 2.00 mm. Strips are no more than 825 mm wide. Manufacturers supply cold-rolled steel in coils and can adapt to the client's wishes such as the maximum and minimum dimensions and coil weights, and the length of the strip also depends on such adaptations. The maximum yield strength is 420 MPa, according to EN 10268 [6], and the hot dip galvanised coating is used [7, 8]. The speed of the rolling process ranges from 6 to 92 m/min. After forming, they are cut to the required lengths by an automatic cut-off tool without stopping the machine. Cut lengths usually vary between 6 and 12 m and can always be adapted to specific requirements. The tolerances in roll forming are usually affected by the section size, product type, and material thickness. All these facts are necessary for automation of the manufacturing process so as to enable mass-production.

The biggest advantage of CFS members is high optimization of cross-section, with a variety of configurations coming from the manufacturing process. Thanks to such varied configurations, CFS members can be structurally extremely efficient and able to suit any specific application. The main advantage is their very low weight to strength ratio. Their limitation also comes from the manufacturing process and is related to wall thickness. In fact, there are many instabilities that do not occur in HRS. These are categorized as local, distortional and global buckling.

CFS members usually come in shapes such as C-sections, Z-sections, I-sections, angles, hat sections, T-sections, and tubular sections (Figure 1). A major function of individual framing members is to carry load, providing structural strength and stiffness. These elements are generally used for roof decks, floor decks, and wall panels.

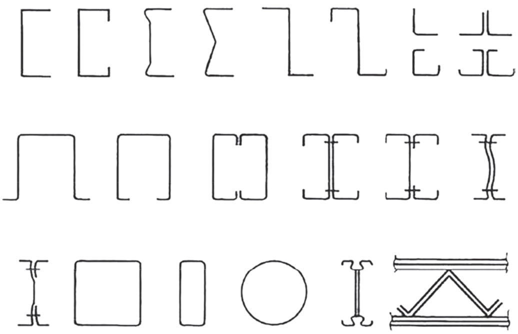

Figure 1. Typical CFS cross-sections [9]

CFS members are primarily used in constructions as structural load-bearing members such as columns, beams and roof trusses. In the light-steel frame (LSF) construction industry, the primary load-bearing components are walls. Walls are usually assembled in panels (Figure 2), which are made of CFS thin-walled members that are used to form load-bearing framing, and gypsum plasterboards with or without insulation infill. Besides the structural load-bearing function, a panel should incorporate insulation and fire resistance function in a single assembly. The framing consists of individual members connected together to form a load-bearing structure. Joints between bearing members transmit forces and moments between members and are conceptualized in such a way to retain the advantage of fast construction, i.e., fast assembly.

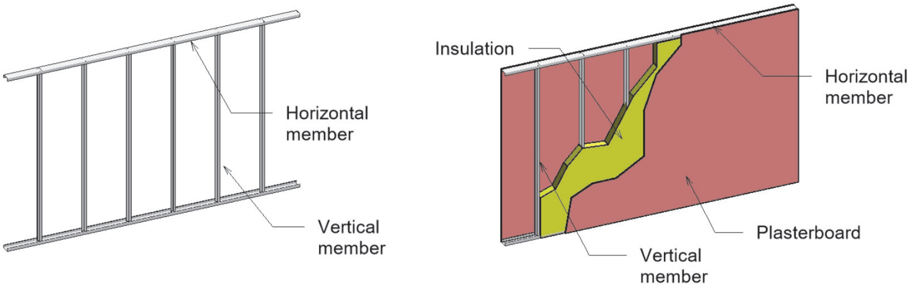

Figure 2. LSF wall panel

Connections in CFS framing construction industry are divided into nine types. They can be made with bolts, self-tapping screws, blind rivets, powder actuated pins, spot welding, puddle welding, clinching, self-piercing rivets, and nailing [9]. Different types of connection are used depending on the application, for example, bolts are used to connect individual members while self-tapping screws, blind rivets, and powder-actuated pines are used to fasten thin sheeting such as plasterboards. Plasterboard and infill materials will also have a significant influence on the behaviour of CFS thin-walled members [10]. Plasterboards protect CFS studs from rapid temperature rise in fire conditions and provide adequate resistance against twisting and buckling [11]. Infill materials are used as insulation and many types are available, e.g., stone wool, glass wool, and various types of polymer foams. They can also influence behaviour of CFS thin-walled members, i.e., as protection from temperature rise in a fire situation, or they can provide some kind of restraint with regard to cross-sectional or member instabilities.

3 Fire requirements

Fire design is an important and essential requirement in the design process for buildings/structures [12]. The main goal of fire protection is to limit risk to people and property. To ensure safety of lightweight steel-framed constructions, adequate regulations have been proposed with regard to their resistance to fire. Within Europe, fire resistance requirements are specified in national building regulations [13]. All buildings must meet some functional requirements, and these are usually linked to the purpose and height of a building [12]. That means that a construction has to have adequate resistance and retain its stability for a reasonable period of time. In a fire event, the building has to perform in a satisfactory manner to limit propagation of fire, to ensure evacuation of the occupants, or to allow safe operations. All these requirements are connected with the time of survival in the standard fire test. A comparison between several national building code regulations (Croatia, Austria, Germany) is presented in Table 1.

In Table 1, the resistance class symbol “R” represents resistance and the number means how many minutes of adequate resistance needs to be obtained in the standard fire test [14]. Reaction to fire class symbol “A” with number represents a material’s contribution to fire spread, where “A1” and “A2” are non-combustible materials. The method for calculating the resistance class is defined in Eurocodes. Thus, the information about thermal actions for temperature analysis is given in EN 1991-1-2 [14], and the method for calculating temperature rise in steelwork can be found in EN 1993-1-2 [15]. If the structural fire performance of elements is based on testing such as in the case of load-bearing walls, the procedure for obtaining a class resistance value is provided at the end of EN 1365-1 [16].

Table 1. Comparison between national building regulations on fire resistance

Part of the building	Country	Building Class				
		1	2	3	4	5
Top floor or attic	Croatia	without requirements	R30	R30	R30	R60
	Austria	without requirements	R30	R30	R30	R60
	Germany	without requirements	R30	R30	R60	R90
Ground floor or other floors	Croatia	R30	R30	R60	R60	R90
	Austria	R30	R30	R60	R60	R90 (6 floors and higher - R90 and A2)
	Germany	without requirements	R30	R30	R60	R90
Underground floors	Croatia	R60	R60	R90	R90	R90
	Austria	R60	R60	R90 and A2	R90 and A2	R90 and A2
	Germany	R30	R30	R90	R90	R90

4 Structural fire performance of LSF

4.1 Design of structural members according to Eurocode

Because of complex behaviour of CFS members, design methods are lagging behind others such as the ones for HRS members [12]. Their specific behaviour requires more studies and, because of specific manufacturing process and variety of possible configurations, they can not be fully covered by standard methods. General performance of CFS differs greatly from that of HRS because of a class of cross-section 4 which is defined in EN 1993-1-1 [17]. The reason for this is high slenderness of thin walls of cross-section and very low torsional stiffness in correspondence with bending stiffness. Moreover, CFS exhibit more instability phenomena which become even more pronounced in extreme temperature situations [18].

The most common fire design method for steel is to design a building for the ambient temperature load, and then to cover the steel members with adequate fire protection to ensure that a specific temperature is not exceeded. Eurocode offers a more flexible approach to fire design, involving a simple consideration of an isolated member approach or consideration of physical parameters coupled with an analysis of the entire building [12]. The fire design Eurocode can be simplified into three components, i.e., characterisation of fire model, consideration of temperature distribution within the structure, and assessment of structural response.

The design approach for CFS members is based on EN 1993-1-1 [17] which gives general rules for the design of steel structures. Additional design rules for CFS members are given in EN 1993-1-3 [3], which gives additional information related to instabilities, in addition to the one for HRS. The EN 1993-1-2 [15] contains an informative Annex E for class 4 (slender) cross-section that specifies temperature reduction factors for the stress-strain relationship of CFS. This method from Annex E suggests that CFS members should be designed according to a method that is a direct extrapolation of the method for room temperature design [19]. Several researchers [20-23] investigated this issue and concluded that design rules given in standards for ambient temperatures can be used to determine capacities of CFS members at elevated temperatures. Also, the European standard is supported by several numerical analyses of CFS members subjected to fire, as proposed by Arrais [24], Couto [25], and Laim and Rodrigues [26]. They concluded that current rules are on the safe side and that they are sometimes even too conservative. On the other side, the method proposed in Eurocode [15] provides mechanical properties reduction factors that largely differ from recent research regarding the manufacturing process, chemical composition, thickness, and grade. Several numerical studies suggest that EN 1993-1-2 [15] is unreliable in some cases.

Couto [25] and Laim and Rodrigues [26] investigated CFS beam members. Couto et al. [25] suggest different design curves in the case of lateral-torsional buckling of slender (class 4) beam cross-sections.

Gunalan et al. [22] investigated compression resistance of CFS columns at elevated temperatures and suggested that more studies should be performed as there is in some cases a lack of non-linear material characteristics in design standards. This concerns non-linearity between the proportional limit stress and yield strength, strain hardening between yield and ultimate strength, and varying yield strength to Young’s modulus ratio [27].

The main method given through EN 1993-1-3 [3] is the effective width method. Thus, structural properties of a particular member can be specified through testing and also through the FE method explained in EN 1993-1-5 [28], Annex C. In addition, laboratory testing results or parametric numerical study results should be provided so that a more realistic analysis of CFS members can be performed. Parametric laboratory testing is cost and time consuming and it is sometimes difficult to find materials with different non-linear properties. Numerical simulation is a cost-effective method to obtain a detailed parametric study [27]. On the other hand, it is essential to set appropriate modelling properties and factors to achieve an accurate structural response. Therefore, simulations like FEM require validation of models based on experimental results.

4.2 Laboratory testing

4.2.1 Laboratory testing of individual members

To get appropriate results from testing, it is essential to subject the specimen to conditions of the environment that it will be used in. EN 1993-1-2 [15] proposes a standard fire test in furnace where temperature depends on the ISO 834 [14] standard fire curve [29]. Also, a group of European standards EN 1365 gives fire testing specifications for individual members and systems such as walls or floors. Members of the structure sometimes require individual approach as they are not part of the structural system like walls or floors. Procedures for testing individual members are defined in European standards EN 1365-3 [30] and EN 1365-4 [31]. These standards specify heating and loading conditions as well as the performance criteria that must be applied to measure time of fire resistance.

4.2.2 Laboratory testing of structural systems

In LSF construction industry, walls and floors are the primary load-bearing components that are covered by parts of EN 1365-1 [32] for walls and EN 1365-2 [33] for floors and roofs. The purpose of these tests is to measure the ability to maintain load-bearing capacity and resist the spread of fire from one side to another. The standard also specifies equipment required to perform a test, test conditions (furnace atmosphere, loading and restraints), test specimen (size, number, design, construction and verification), application of instrumentations (devices for measuring temperature, load and deflection) and test procedure. Finally, it gives performance criteria according to EN 1363-1 [29], while standard requirements for buildings (fire resistance class) can be determined according to EN 1991-1-2 [14] and national building regulations [13].
For example, detailed information on structural performance criteria for vertical load-bearing capacity of the element is given in EN 1363-1 [29], where element failure occurs when one of two criteria connected with deflection is exceeded. The first criterion relates to the limit value of deflection, C_{limit}, equation (1), and the second one concerns the deflection rate, $(dC/dt)_{limit}$, expressed in minutes, equation (2), where h is the initial height of specimen in millimetres.

$$C_{\text{limit}} = \frac{h}{200}\ [\text{mm}] \tag{1}$$

$$\left(\frac{dC}{dt}\right)_{\text{limit}} = \frac{3h}{1000}\ [\text{mm/min}] \tag{2}$$

Specification EN 1363-1 [29] provides strict rules for testing procedures that can be performed only by specialized and certified laboratories.

4.3 FEM simulation

In LFS structures subjected to fire, temperature is usually non-uniformly distributed through individual members. Members are generally a part of structural systems such as walls and floors that are exposed to fire from one side, which leads to non-uniform distribution of temperature through the CFS cross-section. Also, they are assembled in different configurations of sheeting and infill material, which influences temperature distribution, stiffness, and stability. Knowledge about behaviour of individual members at elevated temperatures is essential for understanding behaviour of LSF structural systems in fire conditions. Figure 3.a shows comparison of experimentally and numerically obtained typical failure modes of individual members subjected to compression at elevated temperature. In steel sections, temperature depends on the temperature of the fire compartment, which in the case of the standard fire test follows the standard fire curve ISO 834 [14]. The issue is about transferring heat from fire compartment to the structural element [12]. The governing equation for that is the heat conduction equation and its boundary, which is the basis for the simplified thermal conductivity. The main section factors for conduction are the mass and the surface area of the member exposed to fire. In Eurocode, the simplification is divided into protected and unprotected steelwork exposed to fire [15].

More advanced models of heat transfer need to be applied due to complex heat conduction when CFS members are implemented in LSF systems such as walls and floors [2]. Sheeting and infill materials protect CFS members from direct influence of extreme temperatures and from rapid rise in temperature by distributing the heat through their mass. This gives an opportunity for heat to spread more efficiently and slowly before heating the CFS members. Figure 3.b. shows non-uniform temperature distribution of LSF wall cross-section [34]. This is very important for CFS members that are extremely sensitive in the case of extreme temperatures.

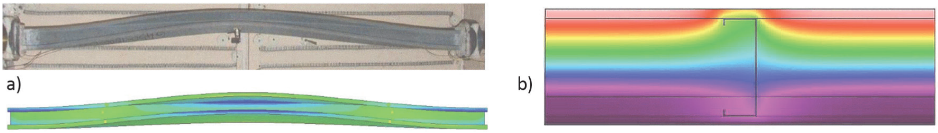

Figure 3. Complex results of FEM simulations: a) Comparison of typical failure modes based on test and FEM [27], b) FEM model for temperature distribution [34]

Another benefit that comes from sheeting and infill materials is that they have positive effects on instabilities of cross-section and member buckling, preventing early collapse of CFS members at 'low' temperatures. Complex simulation of that behaviour necessitates that, for every temperature value, a profile of temperature distribution needs to be obtained along the member, and then structural analysis needs to be performed. In order to obtain valuable results, this needs to be analysed in small temperature intervals. Eurocode [15] also allows for advanced calculation models such as the finite element solution for the determination of thermal and structural performance, which can be performed using software like ABAQUS [4]. To ensure accuracy of the numerical model, the model should be validated with relevant fire test results. Normally, the behaviour of CFS members subjected to fire is simulated with two separate FE models. One model is for the determination of temperature distribution in members, and the other one is used for structural response of the structure. Recent research [35, 36] suggests that a fully coupled FEM model be based on the fundamental physical behaviour (simulation) and that it would be, in fact, more accurate than two uncoupled models. Nevertheless, that model would also be more challenging for simulation and would require more advanced modelling skills, like selecting the most appropriate simulation parameters such as the element type, mesh size, initial imperfection and scale, and temperature profile along the length and in cross-section of the member [15].

5 Conclusion

The main goal of this paper is to offer an insight into the behaviour of CFS members exposed to extreme temperature situations such as fire. Unlike individual members, LSF constructions are assembled by means of several components/materials that have a particular desirable function but also together provide more complex structural behaviour in a fire situation. CFS members assembled in frames have a structural function as main load-bearing components, sheeting function (e.g., plasterboards), and fire protection (and aesthetic) function, while infill materials (e.g., polymer foam) provide for insulation. Connections for all components are conceived for a specific purpose and to enable fast construction and assembly. Along with their main functions, sheeting and infill can also contribute to structural performance of CFS framing, providing restraints for instabilities of CFS members and protecting them from direct fire exposure by lowering heat transfer and preventing rapid rise of temperature. This leads to non-uniform heat transfer, which requires specific numerical calculation of conductivity. Complex behaviour of CFS members, arising from themselves and from other components, requires a very consistent approach for solving structural and thermal performance. Such complex behaviour can be analysed via laboratory testing that is limited and often too expensive, or through numerical analyses (FEM) that are sometimes too complex for interpretation and require advanced knowledge.

Future research on this topic would involve detailed study of relevant FEM simulation techniques. This should be a precondition for establishment of a valuable

FEM model for predicting global behaviour of innovative CFS structural systems (LFS structures). Such preliminary numerical simulation will ensure a good insight into the complex behaviour and planning of the fire testing programme. After performing laboratory testing, it is crucial to question the accuracy of preliminary numerical results, and to perform calibration with experimental results. Such a calibrated numerical model will enable a detailed parametric analysis, which can result in economic optimisation of the entire structural system.

Acknowledgments

The research presented in this paper was conducted within the project “KK.01.1.1.07.0060 - Composite lightweight panel with integrated load-bearing structure” funded by the European Structural and Investment Funds, and the Ministry of Regional Development and EU Funds.

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