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Experimental investigation of post-fire mechanical properties of cold-formed steels

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ABSTRACT

Cold-formed steel members are widely used in residential, industrial and commercial buildings as primary load-bearing elements. During fire events, they will be exposed to elevated temperatures. If the general appearance of the structure is satisfactory after a fire event then the question that has to be answered is how the load bearing capacity of cold-formed steel members in these buildings has been affected. Hence after such fire events there is a need to evaluate the residual strength of these members. However, the post-fire behaviour of cold-formed steel members has not been investigated in the past. This means conservative decisions are likely to be made in relation to fire exposed cold-formed steel buildings. Therefore an experimental study was undertaken to investigate the post-fire mechanical properties of cold-formed steels. Tensile coupons taken from cold-formed steel sheets of three different steel grades and thicknesses were exposed to different elevated temperatures up to 800 °C, and were then allowed to cool down to ambient temperature before they were tested to failure. Tensile coupon tests were conducted to obtain their post-fire stress–strain curves and associated mechanical properties (yield stress, Young's modulus, ultimate strength and ductility). It was found that the post-fire mechanical properties of cold-formed steels are reduced below the original ambient temperature mechanical properties if they had been exposed to temperatures exceeding 300 °C. Hence a new set of equations is proposed to predict the post-fire mechanical properties of cold-formed steels. Such post-fire mechanical property assessments allow structural and fire engineers to make an accurate prediction of the safety of fire exposed cold-formed steel buildings. This paper presents the details of this experimental study and the results of post-fire mechanical properties of cold-formed steels. It also includes the results of a post-fire evaluation of cold-formed steel walls.

1. Introduction

Cold-formed steel members are commonly used as load bearing studs and joists in light gauge steel frame (LSF) walls and floors lined with plasterboards. Inevitably, they can be exposed to fire events as seen in Fig. 1. The temperature rise in cold-formed steel studs and joists under a fire event depends on many parameters such as the fire time–temperature curve, duration of the fire and LSF wall and floor configurations (details of plasterboard linings, insulations and their layouts and stud and joist sections). Recent researches have provided a good understanding of the mechanical properties of cold-formed steels [1–5] and the fire performance of LSF walls [6–10] and floors [11] at elevated temperatures. Upon cooling from elevated temperatures, the plasterboards which protected the cold-formed steel studs and joists can be removed from the steel frames to inspect the damage caused by elevated temperatures. The structural engineer then has to decide if the residual strength of the light gauge steel frame is still adequate for future use by using new plasterboard linings.

The residual strength of hot-rolled structural steel members after fire events was investigated in [12–15] and suitable integrity testing procedures (visual observation, non-destructive testing, destructive testing and rectification) have been developed to verify the adequacy of steel members after being exposed to fire. The primary and most basic form of post-fire integrity evaluation is visual observation prior to the cleaning and removal of furniture and other objects destroyed by the fire. This method is used to identify the location of maximum intensity, as well as temperatures reached during the fire (concrete colour changes, melting glass/plastic etc). Structural members are placed into categories based on their deformation (Category 1: Straight

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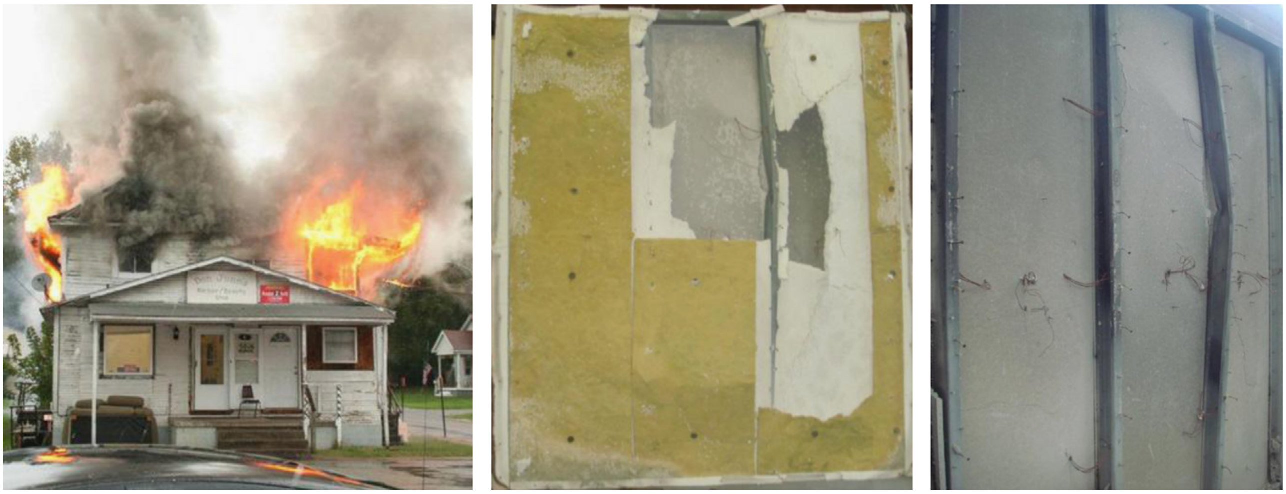

Fig. 1. Fire damaged structures, (a) building fire Image from http://www.firehouse.com/ [Accessed February 10, 2014], (b) LSF wall after fire, (c) Steel frame after fire

members, Category 2: Noticeably deformed and Category 3: Severely deformed [13]). If a hot-rolled steel member is straight (Category 1), then it is presumed that it has not been exposed to critical temperatures and no metallurgical changes have occurred. Members experiencing minor local deformation (Category 2) are generally structurally adequate despite the occurrence of local buckling. Such member deformations can be usually rectified through heat-straightening works. A decision needs to be made whether it will be repaired or replaced. It is likely that Category 3 members have already failed due to the reduction in strength and stiffness of steel at elevated temperatures. The most common form of non-destructive testing used in post-fire evaluation is the surface hardness test. Rapid cooling of austenite steel (above critical phase change temperature) results in hardened steel [13]. Generally, steel that has reached this temperature would not be able to remain straight under its own weight, resulting in a Category 3 member. Therefore, the surface hardness test would generally only confirm the results of a visual inspection. Destructive testing involves the removal of a specimen from the damaged steel and the evaluation of physical properties, residual stresses and grain structures. Rectification of the structure involves compiling the results of the integrity testing and evaluating the next stage. It may be necessary for the building to be demolished if the extent of the damage is too great. Otherwise it must be decided whether certain members will be repaired or replaced. The decision to repair or replace members is based on the economy of the exercise, the accessibility of the member and its importance.

Although the behaviour of hot-rolled structural steel members after a fire event was investigated by many researchers [12–15], the behaviour of cold-formed steel members after a fire event has not been investigated yet. There are also no design guidelines in [16,17] for assessing fire exposed cold-formed steel members. As a result of this limited knowledge on the post-fire behaviour of cold-formed steel members, over-conservative decisions are likely to be made in relation to the residual capacities of cold-formed steel members after fire events. Improved knowledge of these capacities would help engineers make the right decisions. After a fire event, the exposure to extreme temperature variations could have reduced the section and member load bearing capacities of steel members. The main reason for this is the reduction in post-fire mechanical properties (yield strength, elastic modulus, ultimate strength and ductility) of steels.

Current design standards [16,17] do not provide any information on the mechanical properties of cold-formed steels after being exposed to elevated temperatures. Qiang et al. [18] investigated the post-fire mechanical properties of high strength structural steels (S460 and S690) and proposed suitable predictive equations. Outinen and Makelainen [1] also conducted research on various structural steels and reported some post-fire mechanical properties. Hence this paper investigates the residual mechanical properties of cold-formed steels after being exposed to elevated temperatures, and proposes new equations to predict them. Information gained from this research on post-fire mechanical properties will assist engineers in assessing the axial and bending capacities of fire exposed cold-formed steel members prone to various buckling modes while also enabling further development of the cold-formed steel design standards with regards to post-fire cold-formed steel member assessments.

2. Previous studies on post-fire mechanical properties

Outinen and Makelainen [1] conducted an experimental study to determine the mechanical properties of S355 cold-formed steels (nominal yield strength of 355 MPa) at elevated temperatures and after cooling. The specimens were taken from SHS $50 \times 50 \times 3$ tubes after they had been tested at elevated temperatures. The average measured yield strength of the steel before the elevated temperature tests was 529 MPa. The mechanical properties of fire exposed cold-formed steels were compared with the original measured values at ambient temperature. Fig. 2(a) and (b) presents the results as the reduction factor versus exposed temperature where the reduction factor was defined as the ratio of the residual ambient temperature mechanical properties. A noticeable decrease in yield strength was observed along with a decreased elastic modulus. However, the yield strength of S355 steel did not reduce below the nominal value of 355 MPa even after being exposed to 700 °C.

An experimental investigation was performed by Qiang et al. [18] to evaluate the post-fire mechanical properties of high strength structural steels. Two high-strength steel grades, S460 and S690, were investigated in this study (Fig. 2(a)–(c)). Their study revealed that steels exposed to low temperatures experienced no change in their elastic modulus compared to ambient temperature. Both steel grades (S460 and S690) almost fully