FIRE-INDUCED COLLAPSE OF STEEL STRUCTURES:
Basic mechanisms and countermeasures

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Abstract

Single-story steel buildings such as car parks and industrial halls are often characterised by stiff beams and flexible columns and may experience an outward (sway) collapse during a fire, endangering people and properties outside the building. It is therefore a current interest of the research to investigate the collapse behaviour of single-story steel frames and identify relevant structural characteristics that influence the collapse mode.

In this paper, a parametric study on the collapse a steel beam-column assembly with beam hinged connection and fixed column support is carried out under the assumption of a protected column and a standard temperature-time curve on the beam. The study shows that sway collapse can be avoided by increasing either the restrain offered by the column or the load-to-resistance ratio of the beam. It seems possible to extend these results to multi-span frames with bracing system, in case of a fire located on one outer span –situation that represents the worst case for the risk of sway collapse.

With respect to this type of frames, a methodology is proposed for the development of design tables that relate the profiles of the elements to the soliciting load on the beam. By means of those tables, a simple method for the assessment and the countermeasure of unsafe collapse mode of single-story steel buildings can be derived.

Keywords: steel frames in fire, restrain grade, loading rate, thermo-plastic degradation, thermal expansion, thermal buckling, catenary action, pull-back, sway and non-sway collapse.

INTRODUCTION

Current design procedures for structural fire design are aimed at avoiding structural failures under a pre-determined duration of a standard fire, which defines the resistance class of the buildings and may vary significantly, depending on the type of structure and on the occupancy of the premises. If a minimum resistance of 120 min (R120) is required by most European countries for high rise buildings, single-story buildings such as industrial halls may have much shorter resistance time. According to a review of the Italian Committee for Fire Safety of Steel Construction (Pustorino, et al., 2006), the resistance class of industrial halls with low fire load in Europe varies from a maximum of R60 in Sweden and UK, to a minimum of R15 in Belgium, while in other countries like Finland, Germany and Greece no fire design at all is required for these structures.

The reason of the relaxation of the fire safety requirements of certain national regulations lies in the fact that in case of a fire in an industrial hall less severe consequences are expected than in case of a fire in a tall and complex structure, where the egress of the occupants is hampered by the presence of stairs through many floors and where the costs associated to repair or rebuild of the structure would be huge. Nevertheless, the assumption of limited and acceptable. losses for industrial hall fires is only valid in case the collapse of the structure doesn't endanger people and properties on the outside. This circumstance is not unlikely in case of industrial hall collapses, where an outward collapse mode (sway collapse) can be induced by some typical structural characteristics, such as stiff beams and flexible columns.

The problem has been approached by several studies in the last year. However, they are either oriented to explain in details the failure mechanisms of a single steel element under different boundary conditions and thermal actions (Usmani, et al., 2001), (Gillie, 2009), or focused on the design of pitched portals (Song, et al., 2009) and multi-story buildings (Wang, et al., 1995). An attempt to develop a design method for single-story steel frames has been done in the framework of a European research project (EUR 24222, 2010) with respect to pitched portals and lattice steel frames. However, on one side are the proposed empirical formulas not very easy to use, and on the other side the structural characteristics that determine the triggering of one or another failure mechanisms on the other side are not highlighted.
This paper is aimed at describing detail the basic mechanisms that determine the collapse of single-story steel buildings and at identifying the structural properties that influence them. By providing an understanding of the role played by the relevant building characteristics, simple countermeasures aimed at ensuring a safe collapse can be identified and undertaken. Although the results presented in the following refer to a specific frame type, the methodological approach followed in the paper allows for an easy application of the procedure to other frame types and can favour the definition of a general but simple design method for single-story steel buildings in fire.

1 BEHAVIOUR OF SINGLE-STORY STEEL FRAMES IN FIRE

As described in several studies (O'Meagher, et al., 1992), (Bong, et al., 2006) and confirmed by the observation of fire tests (Wong, 2001), the behaviour of steel frames in fire is characterized by an outward movement, driven by the thermal expansion of the fire exposed beam, which may be followed by a pullback, driven by the thermal degradation of the steel heated to high temperatures and subjected to the mechanical loads. The predominance of one or another phenomenon will determine the entity of the outward displacement and, ultimately, the collapse mode.

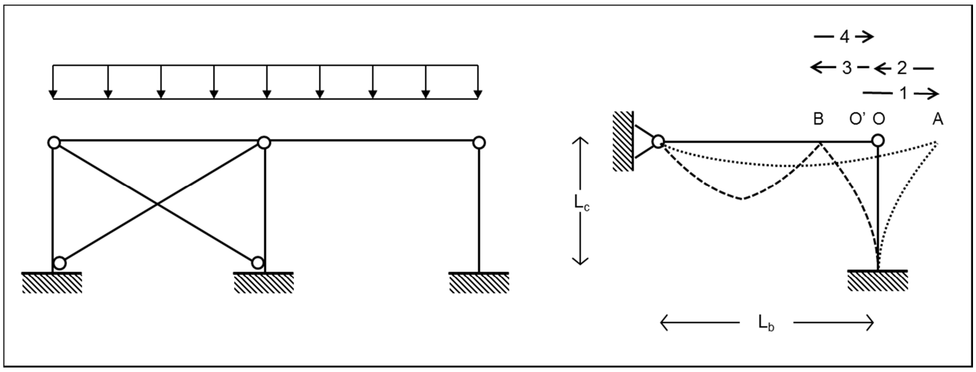

Fig. 1: Two-span braced frame (left) and beam-column assembly (right) with identification of collapse phases.

Collapse phases of a single-story steel frame in fire

In order to better analyse this behaviour and highlight the parameters that play a role in the collapse, reference is made to a simple braced single-story steel frame, as the one shown on in Fig. 1. It is possible to distinguish four phases of the collapse.

Phase 1: expansion / sway collapse

At the beginning of the fire, the temperatures are still relatively low and the mechanical properties of the elements have not significantly degraded yet. In this phase, the effect of the thermal expansion is prevailing on the effect of the mechanical loads. As a consequence, an outward displacement will be experienced by the top of column, which will move from the initial position O' to the maximum outward position A. In the meanwhile, a compressive force will develop in the beam, while the column will be subjected to shear and moment. The relative strength and stiffness of the two elements will determine which element fails first, or cause the outward displacement to exceed a safety limit (SN035a-EN-EU, 2006) in case a displacement criterion is adopted for the definition of the collapse. The overcoming of a displacement limit would occur also in case of a column failure, since as soon as no restrain to thermal expansion is provided by the column, the frame collapses outwards in a sway mode.

Phase 2: pullback

If the beam fails out of compression, the outwards thrust will ceases and the column will start moving backwards towards its rest position O, as the compressive force in the beam will decrease abruptly. As the temperatures get higher the mechanical properties of the steel degrade significantly and a bending failure of the beam will eventually occur. It has to be noted, that in case of a high loading rate of the frame, it is no possible anymore to distinguish between buckling and moment failure, as the beam will experience a compressive-bending failure mode. However, the global behaviour of the frame won't be significantly affected by this and the pullback movement will still be sustained by the formation of a three-hinge mechanism in the beam.

Phase 3: pull-in

After the bending failure, a transition from bending to tensile resistance occurs in beam. The frame moves from the rest position O inwards, as the catenary that develops in the beam slows down the vertical runaway of the mid-span. The predominance of the inward displacement on the tensile stress depends again on the load and the restrain level and could induce either a tensile failure of the beam or a bending failure of the column. In principle, the rise of tensile stresses in the beam, could induce the failure of adjacent elements and trigger a progressive collapse, as in the case of the Oklahoma Building collapse (FEMA 277, 1996) (Giuliani & Prisco, 2008).However, this seems unlikely to occur in case of fire, as the high material degradation of the beam consequent to the high temperatures that characterize this collapse phase would prevent a significant rise of the forces (Yin & Wang, 2004)

Phase 4: relaxation / non-sway collapse

If the beam fails in tension, as typical for frames with fire insulated column, the beam will collapse inside the frame while the column will move outwards towards its rest position, as a consequence of the relaxation of the pull exerted by the beam. If the column fails instead, the beam pull will continue and the frame will collapse inwards. In both cases, an outward collapse is avoided and the frame can be classified as non-sway.

Parametric study

Single story steel frames are often characterised by hinged beam-column connections and by a bracing system for resisting horizontal actions, as the one shown on the left of Fig. 1. In this case, columns are typically quite flexible, as they only sustain the vertical load of one floor. Beams may have instead relatively big profiles, due to possibly high live loads, such as in case of a travelling crane in an industrial hall or the weight of cars on the roof of a car park.

For what said in the previous section, this organization of the structural system may favour a sway collapse, due to a possible low loading rate of the beam, consequence to the likely absence of live loads at the moment of fire, and to the low restrain offered by the slender column to the thermal expansion of the beam. This is especially true if the fire triggers in an outer span of the frame, as only the outmost column would restrain the beam expansion toward the outside.

The study has been therefore restricted to a worst case, represented by a fire in the otmost span of a braced frame with hinged beam-column connections. Under this assumption, the behaviour of a braced frame can be represented by a model of a beam-column assembly, as the one represented on the right of Fig. 1. In order to reduce the number of variables and favour a clear interpretation of the results, the geometry and the material of the frame has been kept constant and the study refers to a 5 m span, 3 m height frame made of S235 steel.

It is expected the behaviour of the frame will vary significantly, depending on weather the column is insulated or not. As such, the two cases should be investigated separately. In the following, only the results related to the case of an insulated column will be presented. In particular, a thermal action corresponding to the standard fire has been applied to the beam, while the column has been considered to remain cold.

Under these assumptions, the initial resistance and stiffness of the elements only vary with the section profiles, and can be directly related to the solely temperature of the beam. Therefore, the parametric study has been conducted with respect to the following aggregated quantities:

- The initial load-to-resistance ratio *LLR* of the beam with respect to bending failure, defined as the ratio between the value of the imposed load p and the elastic limit load p_e:

$$LRR = {}^{p}/_{p_e} \qquad \text{where:} \qquad p_e = 12\,\frac{W_e \cdot f_{s,y}}{L^2} \qquad \text{and} \qquad 0 \leq p \leq p_e \tag{1}$$

- The initial restrain grade of the beam, which depends on the ratio between the flexural stiffness of the column $k_{flex,c}$ and axial stiffness of the beam $k_{ax,b}$. In the following, the effect of this ratio has been accounted by means of a parameter introduced by Pettersson & Ödeen (1978), named γ-factor and defined as:

$$\gamma = 1/1 + \frac{k_{flex,c}}{k_{ax,b}} \qquad \text{where:} \qquad k_{flex,c} = \frac{6 \cdot E_S \cdot I_c}{L^3} \qquad \text{and} \qquad k_{ax,b} = \frac{E_S \cdot A_b}{L} \tag{2}$$

It has to be noted that according to this definition $\gamma = 1$ corresponds to the case of the free expansion of a simply supported beam, while $\gamma = 0$ corresponds to the case of a totally hindered expansion of a double-hinged beam. As such, decreasing the γ-factor corresponds to increasing the restrain grade of the beam.

2 RESULTS

The results of the parametric studies are presented in Fig. 2 with respect to the variation of γ (left column) and of *LRR* (right column). In the Fig., the four phases of the collapse described in the previous section are clearly visible for each of the restrain grade considered. From the Fig. it is also evident that by increasing the restrain grade of the column (i.e. by decreasing the γ-factor), both the horizontal and vertical displacements (indicated with u and δ respectively) decrease, while the sectional solicitations (N and M) increase. As a consequence, the critical temperature of the beam gets lower as the restrain grade increases. The same happens when the *LRR* increases. This means that, by increasing either the restrain grade or the loading ratio, the transition from phase 1 to 2 is anticipated and, consequently, the maximum outwards displacement decreases. It is interesting to notice that the transition from phase 2 to 3, which corresponds to the triggering of the catenary effect, doesn't depend instead on the restrain grade, but only on the loading ratio, as visible by observing Fig. 3.

In Fig. 3 the effect of the variation of the restrain grade (left column) and of the loading ratio (right column) is shown with respect to horizontal and vertical displacements corresponding to: i) the beginning of the fire (situation O', corresponding to the initial position before the fire); ii) the transition between phase 1 and 2 (situation A, when the outward horizontal displacement is maximum); and iii) the transition between phase 2 and 3 (situation B, when the inward horizontal displacement is maximum). In the upper part of the Fig., it is observable that maximum outward displacement decreases almost linearly with an increment of the *LRR*, while decreases much more rapidly with a decrement of the restrain grade (i.e. increment of γ). Therefore, in order to avoid a possible excessive outward displacement, an increment of column section is expected to be more effective than an increment of the beam loading. Furthermore, the sensitivity of the horizontal displacements to γ and *LRR* is much higher than that one of the vertical displacements, which don't vary much with the two parameters in all three situations O', A, and B.

3 METHODOLOGY

The results reported in Fig. 3 refer to an IPE100 beam. The qualitative trend of the displacement with γ and LRR will also apply to different beams; however, the value of the displacements for a given γ and LRR of a bigger profile will be different from that of the IPE100, as the flexural stiffness of the beam will increases. The lower vertical displacements will determine a lower pullback effect and an increment of the outward displacements.

When this displacement becomes significant, even if the column doesn't fail, glasses and other non-structural elements could detach from the façade and endanger people and properties outside the building. It seems therefore sensible to assume a maximum outward displacement $u_{A,lim}$ as sway failure criterion. According to the indication of the British guidelines (P070, 1991), this displacement has been taken equal to 1/100 of the column height, i.e. to 3 cm.

Then, further parametric analyses have been performed for increasing beam profiles. For each profile and each *LRR*, the minimum restrain grade γ_{lim}*(LRR, profile)* corresponding to the achievement of the maximum outward displacement $u_{A,lim}$ has been assessed.

The results are presented in Fig. 4 in the form of an abacus, which provides the limit restrain grade γ_{lim} for a given profile (horizontal axis) and a given *LRR* (identified by a colour). In particular the γ_{lim} is found on the vertical axis in correspondence to the limit height of the area hatched with the colour associated to the *LRR*. This procedure can be repeated for different frames and different fire condition (e.g. frames with fixed connection and uninsulated columns). In this way, a practical design method for assessing a possible outward collapse of a steel frame can be developed and easily integrated in the design practice.

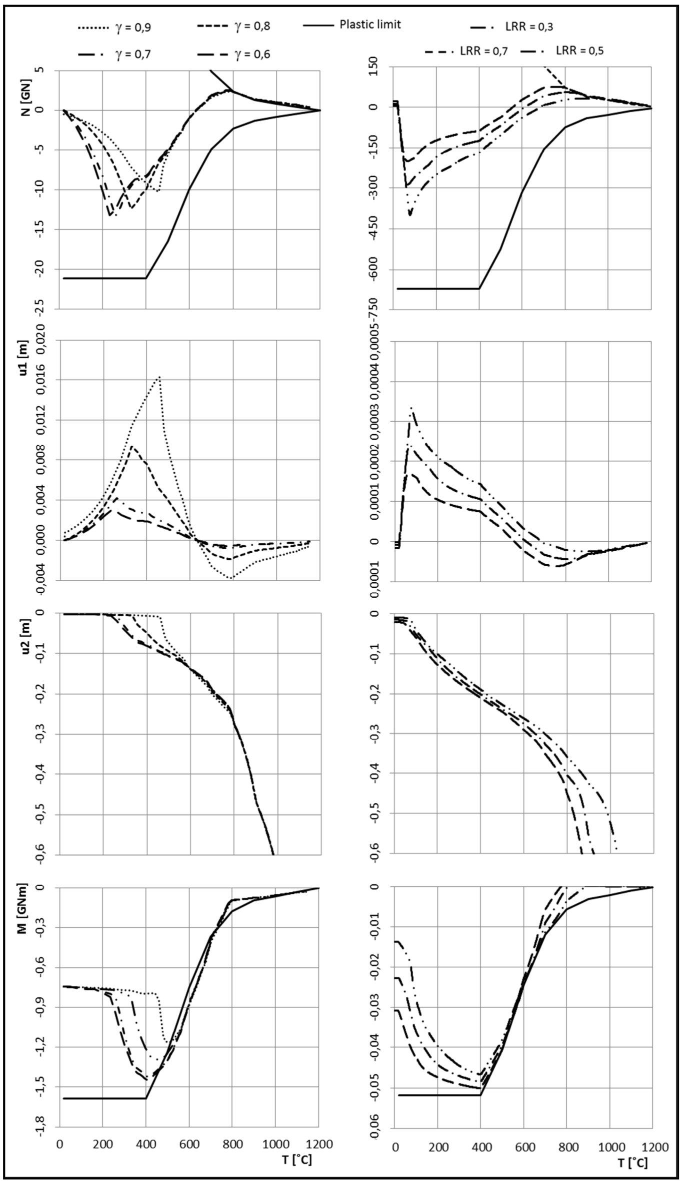

Fig. 2: Increasing restrain grade (left) and loading ratio (right), in term of (top to bottom): horizontal displacement at the top of the column; vertical displacement of the beam mid-span; axial force and mid-span moment in the beam.

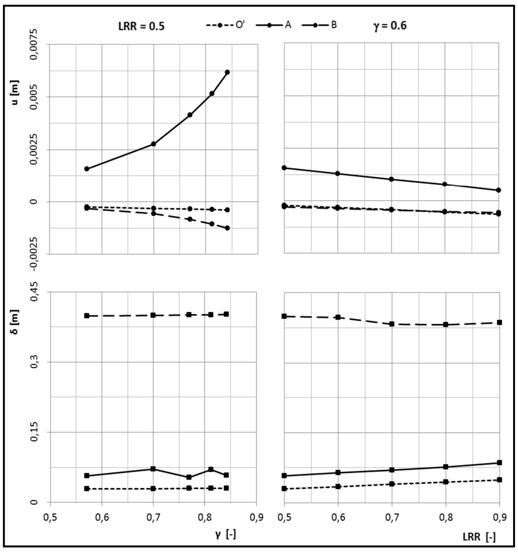

Fig. 3: Horizontal (top row) and vertical displacements (bottom row) in case of variation of γ (left column) and of LRR (right column), with respect to: O' (beginning of fire); A (end of phase 1); and B (end of phase 2).

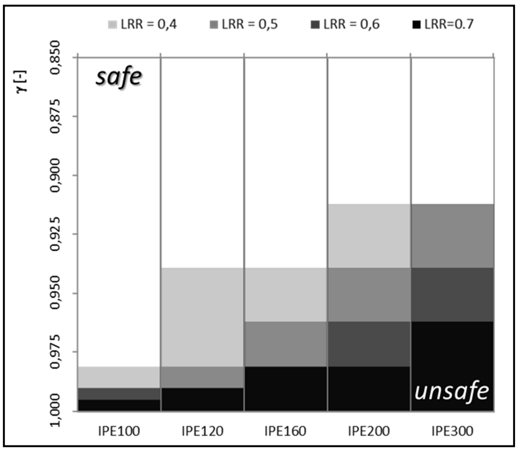

Fig. 4: Abacus for the determination of the collapse mode of a single-story braced frame with hinged beam-column connections and insulated columns fixed to the ground.

3 CONCLUSIONS

In this paper, a parametric study on the collapse mode a steel beam-column assembly with beam hinged connections and column fixed to the ground has been carried out under the assumption of a protected column and a standard temperature-time curve on the beam. The study shows that sway collapse can be avoided by increasing either the restrain offered by the column or the load-to-resistance ratio of the beam.

It seems possible to extend these results to multi-span frames with bracing system, in case of a fire located on one outer span -situation that represents the worst case for the risk of sway collapse. With respect to this type of frames, a methodology is proposed for the development of design Tab.s that relates the geometry of the frame to the vertical load of the beam. The methodology described could be applied to different frame type, such as unbraced frames or frames with fir exposed columns, and lead to the definition of a set of simple rules for a safer and more reliable fire design of single-story steel buildings.

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