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Blast effects on steel columns under fire conditions

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ABSTRACT

Detailed finite element modelling of key elements is necessary to improve the robustness assessment of structures subjected to a coupled effect of fire and blast loads. This paper presents a method for a realistic multi-hazard approach by studying the residual load bearing capacity of steel columns under fire conditions and followed by an explosion. The approach adopts the use of a material constitutive law able to take into account both the strain rate sensitivity and the thermal softening. Explicit nonlinear dynamic analyses are performed using the explicit commercial code LS-DYNA. Results show that the residual load bearing capacity is influenced by the stand-off distance. The time of fire loading at which an explosion is triggered is a critical parameter as well. High strain rates in the typical blast range ($10^2 \div 10^3\ s^{-1}$) are numerically obtained as a consequence of explosions in the close proximity. A comparison with the Eurocode approach is also reported. The results can be of great interest to establish the initial conditions that could potentially lead to the onset of progressive collapse in steel framed structures subjected to a combined effect of fire and blast loadings.

1. Introduction

Structural elements should be able to withstand any accidental action that may reasonably be expected over their entire life. The term *reasonably* is ambiguous, because it is not thinkable to design structures able to withstand any accidental action. However, *the ability of a structure to withstand events like fire, explosions, impact or the consequences of human error, without being damaged to an extent disproportionate to the original cause*, should be ensured. This is the commonly known definition of structural robustness reported on Eurocode 1, Part 1-7 [1].

The progressive collapse is also a widely discussed topic when the robustness of a structure needs to be evaluated, and even if it could be defined *as the spread of local damage from an initiating event, from element to element resulting in the collapse of an entire structure or a disproportionately large part of it*, there is no unique definition of what constitutes a progressive collapse [2–5]. Historically, the progressive collapse became an important topic in structural engineering design after the partial collapse of the Ronan Point Building due to an internal accidental gas explosion [6–8] (London, 1968). During the last decades other buildings were partially destroyed by a progressive collapse, mainly due to terrorist attacks [9,10].

Nowadays it is a matter of fact that the use of explosives by terrorist groups which target critical infrastructures as well as civilians, is becoming a growing problem all around the world. The consequences of such explosions can be directly related to instantaneous life losses. Furthermore, structural failures, e.g. progressive collapses, might be triggered as well. As a consequence, the structural response under explosive loads cannot be ignored and a reliable structural design procedure is required [11].

Among the accidental actions, the EN 1991-1-7 [1] is mainly focused on internal gas explosions in structures where gas is burned or regulated or where explosive gases are stored or transported (e.g. chemical facilities, vessels, bunkers, sewage constructions, energy ducts, roads, rails). The initial guidance in the complex field of protective design was provided in 1969 [12]. Currently, several references for blast resistant design provide a significant amount of information [13–16]. However, none of these references require the consideration of thermal loads either before, during or after the blast threat. Nevertheless, besides the accidental actions, the common definition of robustness [1] takes undoubtedly into consideration the fire loadings. This is because an extended exposure to elevated temperatures may seriously influence the structural performances, leading to possible fire induced progressive collapses [17]. Moreover, it is worth noting that an explosion is defined as a rapid chemical reaction of dust, gas or vapour, which results in the production of very high temperatures and pressure waves. These high temperatures might be the ignition source of a fire. Moreover, in fire situations the high temperatures might be the triggering source of explosions as well. As a result explosions and fire loadings should go hand in hand, or in other

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words the interaction of such accidental actions should be considered.

But, the response of structures under the coupled effect of these loadings has still more criticisms. This is because of a great difference in the structural behaviour under fire and explosion loadings. As stated by Liew et al. [23] the short duration of blast loadings implies that the material should be strain rate sensitive. In fact, blast pressures generally produce high strain rates within structural elements. Typical strain rates during blast events are in the range of $10^2 \div 10^3 \text{ s}^{-1}$ [24]. Moreover, a fire loading is an event of longer duration and is associated with elevated temperatures which lead to a significant strength deterioration in the mechanical properties. In addition, if the problem is coupled, e.g. a fire loading followed by an explosion, the thermal material properties should be coupled with the strain rate material properties. In other words a material constitutive law able to take into account both the strain rate sensitivity and the thermal softening is required.

In this paper a contribution for a realistic multi-hazard approach is presented by studying the blast response of steel columns under fire conditions. The novelty is the implementation of a material constitutive law able to take into account both the strain rate sensitivity and the thermal softening. The parameters of this constitutive relationship were previously determined considering the material properties of the S355 structural steel. The mechanical properties were experimentally obtained performing several tests at high strain rates and in a wide range of temperatures [25,26]. The application of the method is demonstrated by studying the blast response of steel columns under fire conditions. Finally, a comparison between this approach and the approach proposed on the EN 1991-1-7 [1] is reported.

2. Progressive collapse

The coupled effects of fire and blast can be the triggering cause of a progressive collapse. For that reason in the last years some authors have tried to study these combined effects. For example Chen et al. [18] presented a mixed element approach to study the ultimate behaviour of a steel column and a 3-storey steel frame under localised explosion and followed by fire. Izzuddin et al. [19,20] made one of the first attempt to perform an integrated fire and blast analysis. Song et al. [21] and Izzuddin et al. [20] considering both the strain rate and the temperature effects proposed and verified a method for integrated analysis of steel frames subjected to explosion followed by a fire loading. Liew [22] proposed a numerical model for analysing steel frame structures subjected to localised damage caused by blast load and subsequently investigating their survivability under fire attack.

However, as highlighted by some authors [22,27,28], the structural response to impulsive load followed by a fire is mainly studied. As a consequence, the structural response to impulsive load during a fire has still criticisms open to investigation.

2.1. Assessment methodologies

Different approaches to evaluate the structural robustness to progressive collapse can be used. However, only some of these approaches are suitable for a multi-hazard study.

The approach generally adopted for buildings with a high level of risk for consequence of failure is a risk-based method. In particular, this modus operandi is mainly used in situations where the traditional design falls outside the normal limits [29]. Following this approach, the structural robustness evaluation can be based on a probabilistic or risk-based robustness index. A systematic risk assessment could be used for a multi-hazard approach, however this will not be further addressed in this paper. Some references are reported here [4,30-32].

Moreover, other approaches may be followed. For example Ellingwood et al. [33] in their *best practices* to reduce the likelihood of progressive collapse of buildings, reported and described three methods ordered by increasing levels of analytical complexity. These methods can be used for buildings with increasing level of risk for consequences of failure to progressive collapse. These techniques are classified as: indirect design methods, specific local resistance (SLR) and alternate load path (ALP). The last two analyses are commonly known as direct design methods.

The *indirect design method* is a prescriptive approach generally adopted for structures which require a low level of protection. The effects on the structure due to a member loss are not explicitly taken into consideration. For that reason this prescriptive approach is not suitable for a multi-hazard study.

The *alternate load path* (ALP) approach is generally considered as a threat independent approach because a hypothetical damage state is assumed. The hypothetical worst case assumption generally leads to the complete removal of a load bearing element, without considering the threat effects. The designers should check the ability of the whole structural system to find an alternate path, that is to say, if the damaged structure is able to redistribute the loads in order to remain stable. This approach has been the subject of considerable study at Imperial College London [34–38].

The *specific local resistance*, known also as *key element design*, is generally used as method of last resort, where the robustness cannot be assessed by other analyses. This method is considered as a *threat specific approach* because the cause (threat) that triggers a progressive collapse is taken into consideration. This method should be adopted for Class 2B structures [1,39] when the *alternate load path* design cannot assure an adequate redistribution of loads. Furthermore, this approach should be used also for Class 3 structures [1,39] to design critical elements essential for the stability of the structural system. These critical elements should be designed to sustain the gravity load after being subjected to one or more real extreme loading conditions. Even if some critical aspects should be highlighted, this approach is suitable for a multi-hazard analysis. For example, the EN 1991-1-7 [1] states that each critical element should be capable of sustaining an accidental design action of $34\ \text{kN/m}^2$. But it is worth noting that this load is not a specific overpressure resulting from real situations, such as an impulsive load due to an impact or the blast pressure following an explosion. This is undoubtedly a weak point of this approach. This aspect will be addressed in this paper comparing the results obtained following the approach stated on the EN 1991-1-7 and a more complex numerical model.

2.2. Numerical approach

As a matter of fact, a progressive collapse is a very complex situation, where a complex interplay of large deformations, dynamics and inelastic material behaviour are involved. As a consequence conventional structural analyses need to be used with care [34]. Moreover, if the attention is focused on the evaluation of the blast effects on steel columns under fire conditions, the dynamic effects should be considered. The most rigorous and accurate approach is through the use of an explicit nonlinear dynamic analysis. This approach is adopted here.

2.3. Material modelling

The reliability of structural analysis is strongly influenced by the choice of the material constitutive model. As a consequence, in order to improve the numerical simulations, the real mechanical properties of the materials subjected to a combined effect of dynamic and fire loadings should be implemented.

Three different categories of temperature and strain-rate dependent material models can be identified, as physical, semi-empirical and empirical constitutive models [40].

The physical constitutive models are generally based on ideas from dislocation dynamics. The Zerilli-Armstrong [41] constitutive equation is a simple and widely used physically based model. More complex physical constitutive models are for example the Mechanical Threshold Stress (MTS) model [42] and the Preston-Tonks-Wallace (PTW) model [43]. On the other hand, the Steinberg-Cochran-Guinan-Lund (SC-