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Strain rate behaviour in tension of S355 steel: Base for progressive collapse analysis

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ABSTRACT

This paper presents the strain rate behaviour in tension of the S355 structural steel using a modified Split Hopkinson Tensile Bar for the mechanical characterisation at high strain rates (300 s^{-1}, 500 s^{-1} and 850 s^{-1}), and a Hydro Pneumatic Machine for intermediate strain rates (5 s^{-1} and 25 s^{-1}). These data are collected with the intention of setting down the basis for the enhancement of a progressive collapse analysis, that is, by the way, a dynamic event. Results show that the structural steel S355 is strain rate sensitive, keeping its strain hardening capacity with increasing strain-rates. Also the strain energy and the ductility show a marked influence to increasing strain rates. Two of the most used constitutive laws (Johnson–Cook and Cowper–Symonds) are considered and the accuracy of these models is demonstrated. The results can be of great interest for the assessment of robustness in structures where progressive collapse may be triggered by the failure of parallel steel members like, e.g., in the case of cable-stayed or suspension bridges and of large-span 3D trusses subjected to high strain-rate events.

1. Introduction

The progressive collapse is 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. This is a widely discussed topic when the robustness of a structure needs to be evaluated. Historically, this became an important topic in structural engineering design after the partial collapse of the Ronan Point Building (UK) in 1968, where a disproportionate progressive collapse occurred after a partial failure of the 24-storey precast concrete due to an internal gas explosion [1–3]. An additional increase of knowledge has been renewed after the 9/11 World Trade Centre disaster, and due to fresh outbreaks of terroristic threats on civilian targets [4,5]. Others less famous buildings where a progressive collapse took place within these years are the Hyatt Regency Hotel (Kansas City, 1981), the L'ambiance Plaza (Bridgeport, 1987) and the Murrah Building (Oklahoma City, 1995) [6,7].

Many authors focused their attention to the mechanisms involved in the progressive collapse of steel building structures due to the fact that high-rise buildings are usually sustained by means of a steel skeleton system. For example Szyniszewski and Krauthammer [8] presented an energy-based collapse of multi-storey buildings. Szyniszewski [9,10] showed the importance of the deformation energy during progressive collapses. Kwasniewski [11] studied the progressive collapse of a multi-storey building by means of a dynamic procedure, neglecting the strain rate effects. Grierson et al. [12] used a nonlinear quasi-static procedure to evaluate a progressive collapse, while Izzuddin et al. [13] proposed a simplified framework for progressive collapse assessment of a multi-storey building. Kaewkulchai and Williamson [14] demonstrated that a static analysis may not provide a conservative estimate of collapse. Liu et al. [15] studied the effect of the rate of column removal in order to capture the post-blast structure responses. Other researchers, with the intention of studying the vulnerability of structures to disproportionate collapse performed both the experimental [16] and computational [17] investigation of beam–column assemblies with two types of moment resisting connection under vertical column displacement [16] finding a good agreement between experimental and computational results.

Basically two approaches are commonly known for providing resistance to progressive collapse, namely the indirect and the direct methods [18]. The indirect methods use an implicit design to increase the overall robustness, while in the direct methods the designer needs to perform a structural analysis to evaluate the effect of abnormal load events. Two common direct methods

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are known, as the *specific local resistance method* (known also as *key element design*) and the *alternate load path*.

In the first direct method, a single vertical load bearing element should be explicitly designed to sustain, for example, the blast pressure due to an explosion or a impulsive load due to an impact. In the second, commonly preferred for providing resistance to progressive collapse, after a sudden column loss, the designer must check the ability of the whole structure to find an alternate path, that is to say, if the damaged structure is able to redistribute the loads in order to remain stable. Even if the sudden column loss is not identical to a real column damage resulting from a real blast or impact, this scenario is widely considered as a standard dynamic test of structural robustness [13,19].

Another consideration regarding the progressive collapse involves the analytical procedure that can be used to model the problem. Although simplified hypotheses are supposed, like linear static (LS) or non-linear static (NLS) analysis as well as linear dynamic (LD) analysis, the most accurate and rigorous approach for evaluating progressive collapses is through the use of an explicit nonlinear dynamic (NLD) procedure. Marjanishivili and Agnew [20] explained four methods (LS, NLS, LD and NLD) used to perform progressive collapse analyses, Fu [21] analysed a 20-storey 3D structure by means of a nonlinear dynamic analysis, while Powel [22] compared different type of analysis (LS, NLS and NLD) finding that a static approach can lead to very conservative results. Another approach that could be followed is based on the employment of discrete element method (DEM) models. An extensive research in this field has been performed by Masoero et al. [23–25], that demonstrated the DEM's applicability to progressive collapse by simulating the behaviour of 2D and 3D framed structures after sudden damage.

Notwithstanding the fact that a good number of researches are based on the assessment of progressive collapse analysis by means of a nonlinear dynamic (NLD) analysis, only a very limited number of studies are based on the real mechanical properties of the material subjected to dynamic loadings [26]. This lead to the conclusion that a more appropriate dynamic analysis should be based on the real mechanical properties of the materials subjected to high strain rates, because the risk of a progressive collapse depends on how well the material behaviour is captured [18].

The importance of an adequate modelling of material behaviour under high strain rates has also emerged clearly during a series of recent collapses. The "domino effects" originated in oil refineries during the Kobe earthquake (Japan, 1995) put into evidence the crucially different behaviour of different classes of steel used, e.g. for X-cross reinforcement and columns of NLG Horton spheres first subjected to dynamic loading and then to blast and fire. The surprisingly rapid vertical collapse of the WTC towers in 2001 showed the peculiar high-strain rate behaviour of 14-in. steel box columns (mild steel with $f_y = 36\,\text{ksi}$) subjected to hammer-like loading after heat collapse of the airplane-struck floors.

For these reasons and because only in few studies the strain rate sensitivity of the structural steel S355 was studied [27,28], the objective of this research is to characterise in a wide range of a strain rates this typical structural steel. A modified Split Hopkinson Tensile Bar [29] and an Hydro-Pneumatic Machine, both installed at the DynaMat Laboratory of the University of Applied Sciences of Southern Switzerland are used. The main mechanical properties as well as different strain energy densities are reported. In addition the parameters of the most used constitutive laws such as Cowper–Symonds [30] and Johnson–Cook [31] are evaluated. In a future development these constitutive laws will be implemented for the evaluation of a progressive collapse by means of an explicit dynamic procedure.

The paper is organised as follow: *(i) key points in progressive collapse, (ii) description of the experimental techniques at high and medium strain rates, (iii) description of the material characteristics and sample preparation, (iv) results and discussion, (v) constitutive laws and (vi) conclusions.*

2. Key points in progressive collapse analysis

As far as we are concerned the progressive collapse analysis should be based on different aspects.

The choice of the approach. Suitable, and also already studied methods on progressive collapse are energy based approaches [8–10]. From the energetic point of view a progressive collapse could be seen as follow: the removal of a bearing element triggers the movement (displacement) of part of the structure leading to the generation of potential energy. If the structure, or part of it, is able to balance this energy with their internal energy, namely strain energy, due to the material deformations, the system will be in a new stable equilibrium. Otherwise, if the structure is not able to generate enough internal energy, the unbalanced energy (kinetic energy) lead to a movement of the structure and as a consequence the collapse will be triggered. For that reason the first key issue in a progressive collapse is in understanding that is a dynamic event and that the motion is triggered by a release of internal energy due to the loss of a bearing element [20].

Causes that lead to a progressive collapse. In almost all of the current researches the progressive collapse analysis is defined as threat-independent, meaning that the cause of a bearing element failure is not considered [20,32]. For example, even if the structural response should be affected by the time taken to completely remove a bearing element, Liu et al. [15] demonstrated that the effect of the column removal time seems to be not relevant in the analysis, leading to the conclusion that instantaneous column removal is an accurate approach in capturing post-blast structural response. In addition, in many of current researches only uncorrelated effects of high temperatures and dynamic loadings have been considered [33]. Only after the 9/11 tragedy the international community raised significant questions on fire safety and on disproportionate collapse as a result of local failures due to impacts or blasts. As a consequence, the mechanical response of structures subjected to both high temperatures and impact loadings cannot be ignored. This aspect should be analysed in-depth.

The choice of the modelling. The goodness of a progressive collapse analysis depends on how well the material behaviour is captured [18]. In addition, as a matter of fact, the progressive collapse is a dynamic event and a dynamic event require a dynamic analysis. The most accurate and rigorous approach for evaluating progressive collapses is through the use of an explicit nonlinear dynamic (NLD) procedure. Following these considerations, the real mechanical properties of the material subjected to dynamic loadings (high strain rates) [26] are required.

Influence of choices. What is the influence of the aforementioned aspects? For example, if the objective would be to understand the behaviour of a single column subjected to dynamic loading, how much the dynamic effects, the choice of constitutive equations, the choice of the modelling as well as the choice of the right approach are influencing the results? This is still an open question, because in only few studies an evaluation of the committed errors for a simplified progressive collapse analysis based on simplified hypotheses is considered. For example, Pereira and Izzuddin [34], in order to quantify the overstress resistance, proposed a modification of a previous method [13] by considering the material rate sensitivity. An enhancement of the effective resistance by as much as 30% was obtained.