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An enhanced SDOF model to predict the behaviour of a steel column impacted by a rigid body

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The transient dynamic response of a steel beam-column subjected to impact loading is a complex phenomenon involving large localized plastic deformations and non-smooth contact interactions. Exposed to high intensity of the contact force generated from impact, the beam-column may undergo large displacement and inelastic deformation. Previous research has shown that a calibrated elasto-plastic single degree of freedom system is able to reproduce both the displacement and the force time-history of a steel beam subjected to non-impulsive loading or low-velocity impact. In these models, the static force-displacement curve is derived from either experiments or detailed 3D nonlinear analysis. Tri-linear resistance function has been extensively used to reproduce the different stages of the response including catenary effects. A rigorous treatment of such a complex problem calls for the use of non-smooth analysis tools to handle the impulsive nature of the impact force, the unilateral constraint, the impenetrability condition and the discontinuity of the velocity in a rigorous manner. In this paper, we present a non-smooth elasto-plastic single degree of freedom model under impact loading that permits the use of arbitrary resistance function. Adopting the non-smooth framework offers tools such as differential measures and convex analysis concepts to deal with unilateral contact incorporating Newton's impact law. The mid-point scheme is adopted to avoid numerical unrealistic energy decay or blowup. Furthermore, the non-penetration condition is numerically satisfied by imposing the constraint at only the velocity level to guarantee energy-momentum conservation [1]. The explicit expression of resistance functions of the beam that are used in the SDOF model are obtained from a simplified nonlinear static analysis of two beam-column models. In the analysis, a linear relation between normal force and bending moment is assumed for the plastification of the hinges. Two proposals to simplify the explicit expressions of the model's response behavior are given. Performing an energy-based analysis, we predict maximum displacement that is needed to absorb the kinetic energy arising from the impact for different coefficient of restitution. The numerical examples underline the validity of the model by showing good agreement with the predictions of reference models.

1. Introduction

Subjected to transversal impact loading, the column which is a load carrying element of the building may fail due to the high intensity impulsive load produced by an impact. The failure of such a local element can lead to the collapse of an entire structure or a disproportionately large part of it, called progressive collapse. The progressive collapses have usually caused substantial casualties and property losses as reported in [2–5]. Due to these catastrophic consequences, extensive research on the improvement of structural robustness has been carried out to mitigate the risk of the progressive collapse.

Some studies such as in [6–8] perform 3D simulations of the whole frame buildings in order to investigate the collapse response. Other researchers evaluate progressive collapse using experimental methods such as those found in [9–11]. Considering that the 3D simulations and the experimental tests require a considerable amount of time and resources, the problems have also been simplified to 2D model using numerical computation. The work presented in [12] explore the progressive collapse analysis of planar frame structures using beam element formulation incorporating a lumped plasticity model. In that model, the interaction between bending moment and axial force is included, and the degradation of strength and stiffness is considered through the use of a damaged-dependent

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constitutive relationship. On the other hand, Liew and Chan in [13] present a numerical approach for inelastic transient analysis of steel frame structures subjected to explosion loading followed by fire. The fiber beam-column element is used to model steel frame members where material yielding is accounted using a fiber spread-of-plasticity formulation. These models are usually able to accurately predict the inelastic response of the structure. Even so, these methods still require intensive computation capacity and resources to handle the high complexity of nonlinear structural response and the non-smooth nature of contact interaction in the context of extreme loading conditions.

Instead, with the many advantages as listed in [14], the single-degree-of-freedom model has been considered by many researches [15–21] for its ability to provide accurate results while retaining simplicity. For example, Lee et al. in [15] suggest two simplified analysis procedures of welded steel moment frames including a nonlinear static progressive collapse analysis due to column loss and an assessment of the maximum nonlinear dynamic response of the double-span beams above the removed column. In their method, the resistance functions are obtained from parametric studies using ABAQUS program for the values of span-to-depth ratio of an H-section: 10, 15 and 20. Yu and Guo in [16], on the other hand, develop a nonlinear single degree of freedom model for the transient dynamic response of substructures above the removed column using a tri-linear resistance function that describes the catenary action and the softening resistance. Nonetheless, the resistance functions in those models are either obtained from experimental tests or from fully nonlinear 3-D simulations, which are not applicable for design purposes. The traditional formulation for steel beam-column under transverse loading such as [17] considers only flexural behavior while the influence of the axial force on the bending moment is ignored. Such consideration may become over-unrealistic for the response of a restrained steel beam-column that undergoes large displacement under extreme loading such as impact. Yin and Wang in [20] present the development and the validation of a simple analysis method of the catenary action in steel beams at elevated temperatures. An important assumption of the method is the beam's deflection profile that changes according to the beam's loading condition and end rotational restraint. In addition, the model includes the catenary effect in an approximate manner with the axial force being computed without considering the bending moment while the latter is calculated from the axial load-bending moment interaction curve. Aside from that, this method considers only symmetrical beam models under distributed transverse load without initial compression force. Izzuddin in [21], on the other hand, presented a simplified explicit model for an axially restrained simply supported beam subject to extreme transverse loading at mid-span. The model is able to account for membrane effect through a linear relation between axial force and bending moment. Given the ability to provide explicit analytical solutions, Izzuddin's model has attracted researchers and design offices interested in the practical applications. For example, Naji and Irani in [22] describes a formulation of a simple model to evaluate the displacement of the removed column point by adopting Izzuddin's model for static response. Moreover, Jian and Zheng in [23] proposed a simplified model for a static analysis of progressive collapse response of RC beam-column substructures under mid-span point load based on Izzuddin's approach. They propose three stages of response: beam mechanism stage, transient stage and catenary mechanism stage. Izzuddin's model is indeed useful and innovative, but it is currently available for only a simply supported symmetrical beam without initial compressive forces. Furthermore, the model uses a rigid mechanism assumption in order to compute the plastic rotation at the hinge.

This paper presents a new nonlinear SDOF model of a steel column impacted by a rigid mass. The model considers a clamped-clamped column, fixed at one end and attached to an elastic spring at the other end which is also loaded by a constant compressive force. This column is also subjected to a transversally arbitrary located point force. The material and geometry nonlinear behavior of the SDOF model is reproduced using a standard one-dimensional elasto-plastic constitutive model whose parameters are identified from the resistance functions. Assuming that the formation of the plastic hinges occurs at critical locations, the plastification of the hinges follows the normality rule with a linear yield surface that accounts for the interaction between M and N. Taking into account the catenary effect and large displacement, explicit analytical expressions are derived. On the other hand, impact is a very stiff problem involving unilateral constraint, discontinuity of velocity and impulsive forces. This calls for a sound and rigorous framework of the non-smooth dynamics [24–26] to derive the equations of motion using differential measures and convex analysis tools. Velocity jumps at impact instances are described using Newton's impact law by means of a restitution coefficient to account for possible energy losses during the collisions. Exhibiting discontinuity in time, the smooth equation of motion is no longer valid to represent the motion at the instances of impact. For that case, the impact equation must be written. A differential measure is then introduced to write a set of differential measure equations to describe the impact and impact-free phases of motion. The midpoint rule, which is an energy-momentum conserving scheme, is adopted to solve the equations of motion in order to avoid unrealistic dissipation of energy that results from numerical computations. Furthermore, the non-penetration condition is numerically satisfied by imposing the constraint at only the velocity level to guarantee energy-momentum conservation [1]. The energy-based analysis is also performed to approximate the maximum displacement of the beam-column required to absorb the kinetic energy generated from the impactor. The models are also validated against a 2D co-rotational beam element [27] and a 4-DOF simplified model of steel column [28].

The rest of the paper is organized as follows. The presentation of the analytical models is given in Section 2. Section 3 introduces the development of the force-displacement expressions for the response of Model 1. Two suggestions on the simplifications of those expressions and numerical examples are also provided for this model. In Section 4, the force-displacement relations for the response of Model 2 is presented. An investigation of the SDOF system under impact is carried out in Section 5 whereas the methodology to obtain the maximum displacement is given in Section 6. Furthermore, Section 7 presents the numerical applications of the models. Finally, Section 8 is devoted to the conclusions of the paper.

2. Presentations of analytical models

For a slender column under transverse load, plastic hinges can be expected to form at critical locations (see Fig. 1(a)). In the present work, two models of a steel column are described; the column consists of rigid bars connected by generalized elasto-plastic

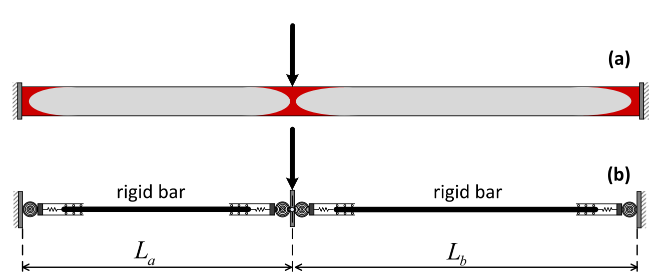

Fig. 1. (a): Formation of plastic hinges. (b): Model of the generalized elasto-plastic hinge.