3D NUMERICAL ASSESSMENT OF THE PROGRESSIVE COLLAPSE RESISTANCE OF A SEISMIC-RESISTANT STEEL BUILDING WITH POST-TENSIONED BEAM-COLUMN CONNECTIONS

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1. ABSTRACT

This paper presents the numerical assessment of the progressive collapse resistance of a seismic-resistant steel building with post-tensioned beam-column connections. The numerical simulations are carried out in 3D under a loss of column scenario. The 3D model considers the effect of the composite slab, where composite beams and their shear connectors are modeled with a combination of shell, beam and nonlinear connector elements. All the beam-column and beam-to-beam connections are modeled using nonlinear connector elements with appropriate failure criteria. Moreover, the steel frame for which a column is removed is modelled in full detail with the aid of 3D solid elements to accurately capture its local and global nonlinear behavior. Nonlinear static analyses are carried out to identify the failure modes of the building under a sudden loss of column scenario and investigate the effect of the floor slab on the overall progressive collapse resistance.

2. INTRODUCTION

Conventional seismic-resistant structures, such as steel moment-resisting frames (MRFs), are designed to experience significant inelastic deformations under strong earthquakes [1]. Inelastic deformations result in damage of structural members and residual interstory drifts, which lead to high repair costs and disruption of the building use or occupation. The aforementioned socio-economic risks highlight the need for widespread implementation of minimal-damage structures, which can reduce both repair costs and downtime. Amongst others, steel frames equipped with self-centering beam–column connections with post-tensioned high strength bars ([2], [3]) demonstrated their superior seismic performance, *i.e.* in minimizing the damage in the main structural components and in providing self-centering capability even under strong earthquakes.

However, specialization of the structure in order to improve the seismic performances should not affect their capability to resists other types of hazard and multi-hazard considerations are required ([4]).

Amongst others, man-made hazards deriving from events such as fire, explosions or impact gained the attention of many researchers in the last decades because of the possibility of progressive collapse [5]. Progressive collapse of a structure occurs when the failure of a structural component, leads to the collapse of the surrounding members, promoting additional or even global collapse.

Despite the relatively large body of research on the seismic behavior of self-centering moment resisting frames (SC-MRFs), their robustness under a column loss scenario is not thoroughly studied. SC-MRFs are placed at the perimeter of a building as lateral force resisting system and, hence, they are prone to accidental events that could produce the loss of one or more columns. Previous research on robustness of steel concrete composite frames focused on their 2D behavior or on the isolated behavior of their slab by itself. The present paper focuses on the robustness of SC-MRFs under a column removal scenario accounting also for the contribution of the 3D membrane effects of the slab based on 3D finite element models developed in ABAQUS.

3. CASE STUDYING BUILDING

A 5-story SC-MRF using post-tensioned (PT) connections with web hourglass shape steel pins (WHPs) [3] is used as the prototype building. The plan view and elevation are shown in *Fig. 1*. The frame uses perimeter SC-MRFs to resist seismic loads, while the interior frames are designed for gravity loads only. Two high strength steel bars located at the mid depth of the beam, one at each side of the beam web, pass through holes drilled on the column flanges. The bars are post-tensioned and anchored to the exterior columns. WHPs are inserted in aligned holes on the beam web and on supporting plates welded to the column flanges. Energy is dissipated through inelastic bending of the WHPs while the self-centering capabilities are ensured by the gap opening mechanism and the presence of the PT bars. More details on the case study building are reported in [3] and [6].

4. VALIDATION OF THE NUMERICAL MODELS

Numerical models are built in ABAQUS [8] to simulate the behavior of the basic structural components (*Fig. 2*) i.e. fin plate connections, steel-concrete composite beams, and the SC-MRFs and are validate against experimental results.

4.1 Validation of the steel-concrete composite beam

For the validation of the numerical model of the composite beam, an experimental investigation by Vasdravellis et al. ([7], [9]) of simply supported beams under a single point load is considered. Full geometrical and material properties are given in that reference. The steel material of the beam is simulated by using the elasto-plastic stress-strain law with hardening. An elastic perfectly-plastic model was used to simulate the material response of the reinforcement. The concrete is modeled by using the concrete damage plasticity model in ABAQUS. The concrete stress-strain curve in compression follows a modified Hognestad stress-strain relationship [10] while the modulus of elasticity of the concrete E_c is taken according to EC2 [11]. For the validation of the numerical model, the experimentally determined tensile strength is considered. For the progressive collapse investigation, the mean tensile strength f_{ctm} is taken according to EC2 [11]. An idealized behavior in tension is assumed for the concrete with a linear softening and a residual tension strength of $0.1f_{ctm}$ starting at strain equal to 0.05.

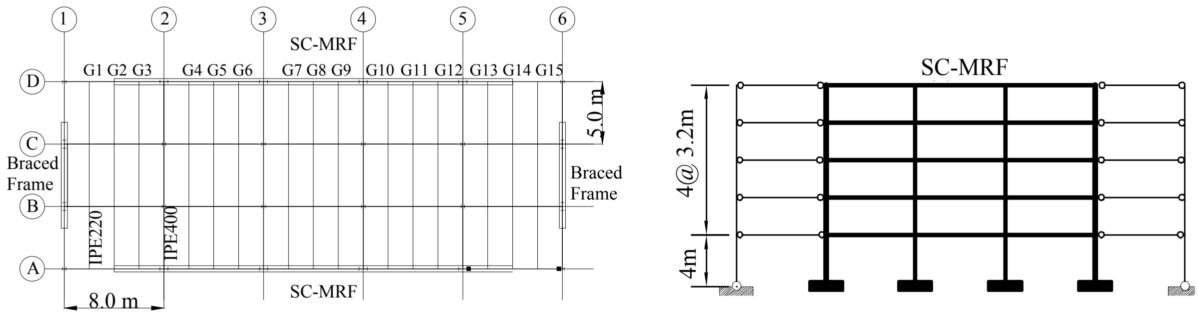

Fig. 1: a) Plan view and b) elevation view of the prototype building

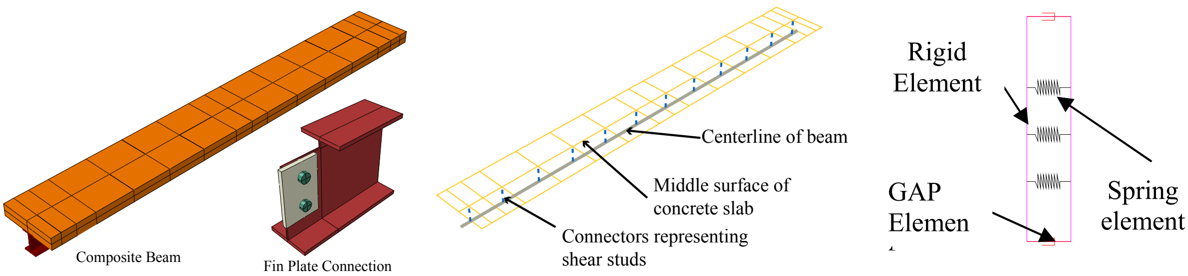

Fig. 2: (a) Composite beam & fin-plate connection of a beam; and mechanical idealization of (b) composite beam and (c) fin plate connections

Connector elements (of Cartesian and Align type) connecting the middle surface of the concrete slab to the middle surface of the beam elements are used to model the shear studs. An elastic-perfectly plastic behavior is assumed for the shear connectors. Experimental strengths are used for the validation of the numerical models of the composite beams. Nominal strengths according to EC4 [15] are used in the progressive collapse simulations. Maximum slips obtained from push-out tests are used in the numerical analyses to consider fracture of the studs.

Fig. 3 shows a comparison between numerical and experimental results for the case of sagging and hogging moment, respectively. The simplified numerical model can capture the sagging and hogging behavior of the composite beam. The larger force capacities exhibited in the hogging moment can be contributed to the idealized behavior that was adopted for the concrete in tension.

4.2 Validation of the fin-plate connections

The experimental results from Thompson [12], described in detail in [13], have been used to validate the simplified numerical model for the fin plate connection. The fin plate connection is modelled using the component method where at each bolt level a spring is considered having stiffness and strength that described best the combined behaviour of the fin plate, the beam web and the bolt. The stiffness and strength of these springs are estimated according to EC3-1.6 [14] while the ultimate deformations according to [15]. Gap-like springs are attached at the beam flange levels to account to contact phenomenon at large displacements. *Fig. 4* shows the numerical results of a four-bolt fin plate connection accompanied with the corresponding experimental results. A good agreement can be observed for the two cases.

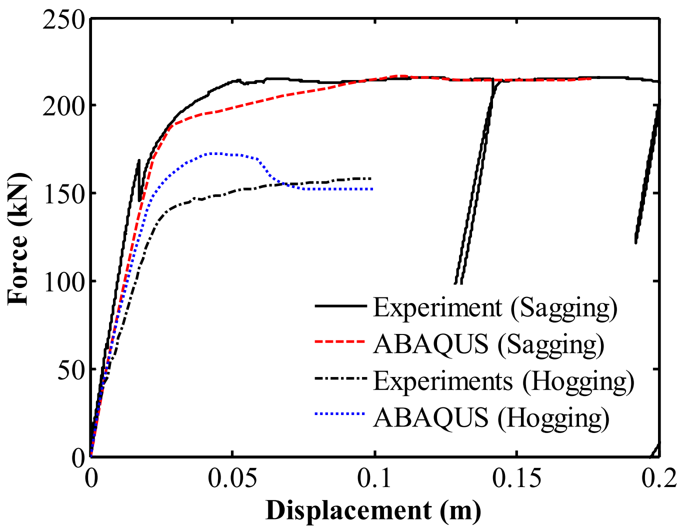

Fig. 3: *Comparison of numerical and experimental results for the composite beam*

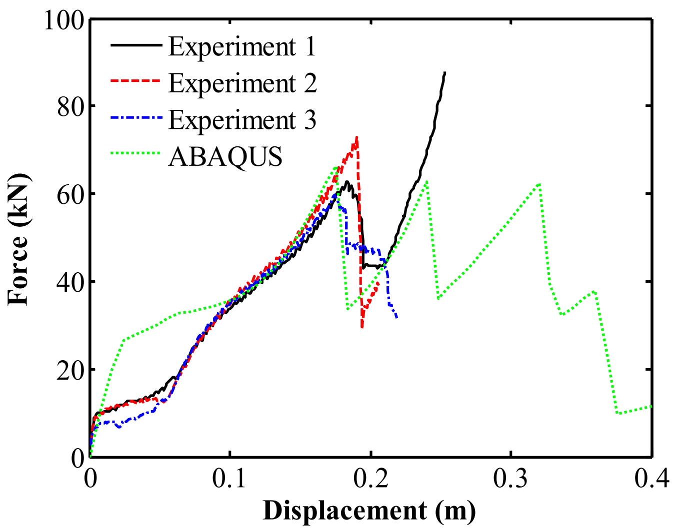

Fig. 4: *Comparison of numerical and experimental results for the fin-plate connection*

4.3 Validation of the PT connection

The model of the PT connection with WHPs used in the SC-MRF of the case study building, has been validate elsewhere [16] and found capable in capturing the cyclic behaviour and the local and global failure modes up to excessive imposed deformations.

5. FINITE ELEMENT MODEL OF THE BUILDING

The ABAQUS finite element model of the first floor of the prototype building provides insights in the progressive collapse resistance of SC-MRFs (*Fig. 5*). Only one of the two SC-MRFs, which exhibits column failure, is modelled using eight-node linear brick element (C3D8R) while the PT bars are modelled with truss elements. All the rest of the structural members (beams, columns, braces) are modelled with beam-column elements (B31). The concrete slab is modelled with shell elements (S4R). Fin plates and shear studs are modelled using connector elements as explained in the previous sections. Appropriate contact interactions are considered for the SC-MRF and the contact of the slab to the main beams. A 120 mm-thick slab reinforced with a N12/150 mm top and bottom rebar mesh is considered. A 'bolt load' is used to model the initial post-tensioning force in the PT bars. A nonlinear static analysis is first performed to apply the initial force in the PT bars. The upper ends of columns are modelled as pinned representing inflection point in steel column [17]. Both gravity columns with pinned supports and SC-MRF columns with fixed support extend up the half-height of the second floor. In a subsequent nonlinear static analysis, the support of the column that is failed is removed and a vertical downwards displacement is applied to the top of the column. The standard 'Full Newton' solution technique is adopted together with an automatic incrementation scheme for the application of the loading.
Fig. 6 shows the deformed shape of the building when the failed column reaches a displacement equal to 1.60 m. *Fig. 7* shows the force versus vertical displacement at the removed column resulting from the nonlinear static analysis for three structural configurations: (i) the SC-MRF is modelled on its own; (ii) the first floor is modelled but no slab is included; and (iii) the first floor is modelled including the concrete slab and its composite action with the steel sections. The horizontal axis represents the vertical displacement of the removed column and the vertical axis the associated reaction load. It can be seen that the effect of the beams and the fin plate connections is negligible. The strength of the second structural configuration is the same as the first configuration. The effect of the composite action of the concrete action and the secondary beams, however, significant since its contribution increases the overall resistance of the system by 30%.

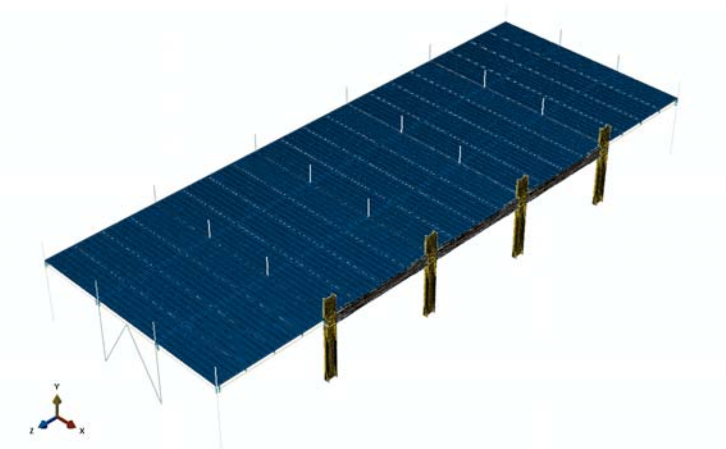

Fig. 5: Finite element model of the building

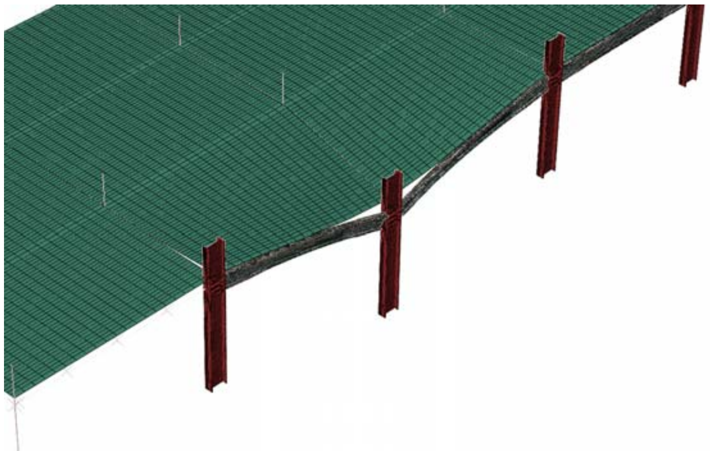

Fig. 6: Deformation state of the building after the column removal (1.60m displacement)

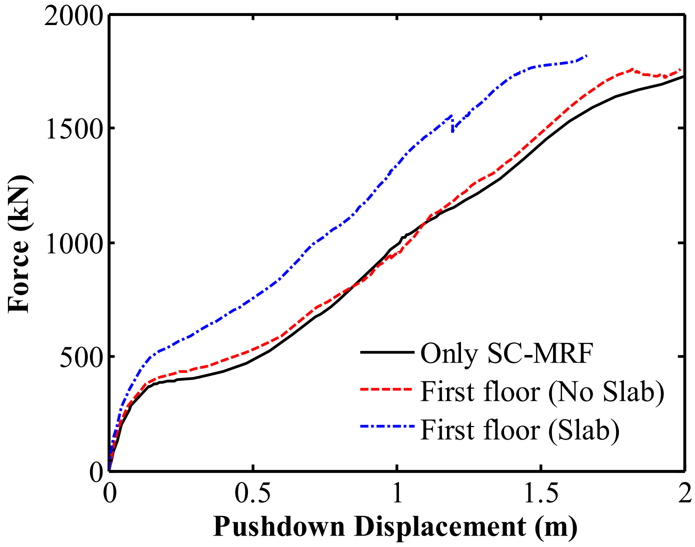

Fig. 7: (a) Load-displacement curves from nonlinear static analyses

6. CONCLUSIONS

This paper studied the progressive collapse resistance of a steel building with SC-MRFs. Simplified numerical models were built and validated against experimental results for the composite slab and the fin plate connection. Static nonlinear analyses were performed to study the robustness of the building against a sudden column removal of the SC-MRF. It was found that the contribution of the steel beams alone is negligible, however the effect of the composite slab is significant and could overcome the 30% of the overall progressive collapse resistance of the building.

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ΠΕΡΙΛΗΨΗ

Σε αυτό το άρθρο παρουσιάζεται μια αριθμητική διερεύνηση της αντοχής έναντι κατάρρευσης ενός μεταλλικού κτιρίου με συνδέσεις δοκού υποστυλώματος αυτο-επαναφερόμενης συμπεριφοράς. Η ανάλυση λαμβάνει υπόψη το τρισδιάστατο φορέα του πρώτου ορόφου του κτιρίου. Το τρισδιάστατο μοντέλο λαμβάνει υπόψη την επίδραση της σύμμικτης πλάκας, η οποία προσομοιώνεται με ένα συνδυασμό στοιχείων κελύφους, δοκού, και μη γραμμικών ελατηρίων. Πέρα από τις συνδέσεις δοκού υποστυλώματος αυτό-επαναφερόμενης συμπεριφοράς, όλες οι υπόλοιπες συνδέσεις δοκού-δοκού και δοκού-υποστυλώματος είναι συνδέσεις διάτμησης και προσομοιώνονται χρησιμοποιώντας μη γραμμικά ελατήρια με κατάλληλες συνθήκες αστοχίας. Επιπλέον, το μεταλλικό πλαίσιο το οποίο υφίσταται την απώλεια υποστυλώματος προσομοιώνεται με τρισδιάστατα στοιχεία ελαστικότητας. Για τον προσδιορισμό των μορφών αστοχίας του κτιρίου και τη διερεύνηση της επίδρασης της σύμμικτης πλάκας στην αντοχή του κτιρίου έναντι σταδιακής κατάρρευσης πραγματοποιούνται μη γραμμικές στατικές αναλύσεις. Η επίδραση της σύμμικτης πλάκας είναι αρκετά σημαντική με συνεισφορά η οποία μπορεί να ξεπερνά και το 30% της ολικής αντοχής.