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Seismic performance and fragility functions of a 3D steel-concrete composite structure made of high-strength steel

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ABSTRACT

This paper provides insight into a probabilistic seismic demand analysis of a steel-concrete composite structure made of a novel type of high-strength steel moment resisting frame, to be used either in a seismic risk assessment or a fully probabilistic Performance-Based Earthquake Engineering (PBEE) framework. The application of the PBEE methodology with a full probabilistic character is able to rigorously evaluate the seismic risk to which a structure may be exposed, as well as to quantify economic losses, including both direct -repair, reconstruction costs, etc.- and indirect costs -downtimes, etc.-. In this respect, the knowledge of seismic fragility functions is paramount. Moreover, due to the dynamic complexity of the examined structure caused by irregularity in elevation and different lateral-force resisting systems in the two main directions -moment resisting frames (MRFs) and concrete shear walls- the seismic behaviour is not straightforward to foresee. Therefore, two separate 2D analyses along the building main directions may not suffice to identify the actual dynamic response and, consequently, a 3D comprehensive probabilistic seismic demand analysis was performed by taking into account the earthquake incident angle. In order to exploit the inherent overstrength of non-dissipative members, consistently with the capacity design philosophy, the structure, that is a representative example of a realistic office building, is characterised by a newly-conceived type of moment resisting frame made of high-strength steel circular columns filled of concrete and of mild steel beams. In this respect, a nonlinear 3D FE model was developed and calibrated on experimental tests performed on both beam-to-column and column-base joints that formed MRFs. A multiple incremental dynamic analysis (MIDA) was then performed with two groups of bespoke accelerograms characterised, on one hand, by large magnitude and large distance and, on the other hand, by near-source effects. The earthquake incidence angle was also considered and, to decrease the number of simulations, the accelerogram-incident angle pairs were selected by means of the Latin hypercube sampling (LHS) method. The relevant seismic analyses highlighted the need to include the incident angle to better characterise its dynamic behaviour. Hence, the seismic fragility functions were built both for damage and collapse limit states considering both the maximum interstorey drift ratio as engineering demand parameter and different intensity measures as well as the incident angle randomness. The results showed that peak ground displacement entails a more efficient probabilistic model because the dominant structural dynamic behaviour was governed by MRFs characterised by fairly long periods.

1. Introduction

1.1. Background and motivation

In the last years, there has been a growing trend in the use of high-strength steel (HSS) in tubular structures thanks to the publication of EN1993-1-12 [1] that extended the use of structural steel up to grades S690Q/S700MC. Nonetheless, EN1993-1-12 imposes many limitations at the material, structural and design level due to the limited knowledge of its actual behaviour. The use of HSS can be advantageous in seismic design when employing the capacity design philosophy for non-dissipative elements owing to its inherent overstrength. Thus, columns in MRFs designed in HSS and beams in mild steel can represent an effective solution for structures located in moderate seismic prone zones, when the limitation of lateral displacements is not dominant. For this purpose, in order to promote the use of HSS circular sections in buildings, the Research Fund of Coal and Steel (RFCS) project called ATTEL was funded, with the aim to investigate both seismic and fire

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Nomenclature

A	wall gross area
EI	flexural stiffness of the beams
G	shear modulus of the walls
J_w	torsion constant of the wall sections
m	number of the IM values
M	magnitude
n	number of input accelerograms
PGA	peak ground acceleration
PGD	peak ground displacement
PGV	peak ground velocity
R	epicentral distance
$Sa(T_1;5\%)$	spectral acceleration at the first period with 5% equivalent damping ratio
Z	limit state exceedances

behaviour [2,3]. To exploit the inherent overstrength of non-dissipative members within the project, a novel type of moment resisting frame with HSS column filled with concrete and mild steel beams was conceived. Both cost savings of the proposed solution and the capability of beam-to-column and column-base joints to exhibit a favourable seismic behaviour for a medium ductility class was demonstrated in [4]. The relevant reference structure is representative of a realistic office building.

In the last fifteen years, the adoption of the probabilistic PBEE methodology has become popular [5–9] and the availability of seismic fragility functions of a particular structural typology or component is crucial for both risk assessment and/or a probabilistic PBEE application [10]. For instance, a fragility curve can express the probability of exceedance of an engineering demand parameter (EDP) given -conditional- an intensity measure (IM). Thus, the choice of interstorey drift ratio as global EDP can directly be assumed as a damage measure (DM) [10]. In this respect, the Hazus database [11] already contains a number of fragility functions for various structural typologies and components. However, if the structural typology/component is new, they have to be determined. The computation of seismic fragility curves typically requires several nonlinear dynamic analyses with seismic input representative of the structure site. Due to the aleatory nature of ground motions a set of accelerograms has to be selected among: (1) artificial waveforms; (2) simulated accelerograms; and (3) natural records [12,13]. Natural accelerograms are the most direct representation of ground motion; in fact, they contain amplitude characteristics, frequency content, energy and duration of actual events. Therefore, the use of natural accelerograms is spreading as input to the nonlinear structural dynamics. This happens due to easy availability of online Strong Motion Databases [14,15], but also because it is possible to get an accurate, statistically correct estimate of the seismic demand.

Generally in design practice, when plan regularity criteria are met, simplified 2D structural analyses are performed [16]. In that case, the structure is analysed with seismic loading acting along two orthogonal directions, typically the two axes of symmetry or two orthogonal directions along the main building directions. Conversely, when a nonsymmetric irregular structure is examined, the dynamic behaviour becomes more complex and coupling between the two main directions owing to torsional effects is likely to occur; as a result, a more complex 3D model is required [12,16]. Moreover, when a structure is made of two different lateral-force resisting systems in the two main directions, due to sensitive differences in dynamic properties, the dynamic response of the whole system is less straightforward to predict. In fact, an increased dynamic complexity reduces considerably the intuitive understanding of the structural response. For instance, this can occur for structures composed of a steel MRF in one direction and concrete shear walls in the other [4], a solution conceived to limit column strength and reduce complexity of beam-to-column joints. As a result, for structures with a certain degree of irregularity or characterised by different lateral-resisting systems in both directions, as composite structures, a separate analysis along the two main building directions may not suffice to accurately capture the dynamic behaviour; thus, a 3D analysis is needed.

The application of two horizontal components along the main building directions may not lead to the most unfavourable case, because the influence of the incidence angle of a seismic event can be significant. However, the analysis is rarely performed considering a variation of the incident angle of seismic motion. Works related to this topic were carried out by a few researchers [17–26]. In particular, Wilson [19] investigated the suitability of the 100–30% and 100–40% combination rules. Rigato and Medina [20] examined the seismic behaviour of asymmetric and symmetric inelastic structures characterised by different periods of vibration. They showed that ductility demands are, in general, underestimated when horizontal components are applied along the principal directions of a structure. Athanatopoulou et al. [21] proposed a formula valid for elastic structures to determine the critical incidence angle. MacRae and Mattheis [22] analysed the inelastic response of a 3D steel structure subject to near-fault motions by varying the incidence angle with negligible torsional effects. Lopez et al. [24] proposed a method to determine the critical angle of seismic incidence and the corresponding peak response of discrete, linear structures subjected to two horizontal components applied along arbitrary directions and to the vertical component of earthquake ground motion. Moreover, Lopez et al. [25] presented an explicit formula to calculate critical value of structural response due to both principal horizontal components acting along any incident angle and the vertical component of ground motion. In [26], Skrekas and Giaralis investigated the influence of both near-fault effects and incident angle of earthquake waves by means of an incremental dynamic analysis (IDA) on the seismic response of a typical jack-up offshore platform. They demonstrated that the “pulse-like” fault normal component poses much higher seismic demands compared to the fault parallel component. More recent works reported in the literature on the seismic behaviour of structures that include incident angle were drawn up by Lagaros [17,18]. However, they refer to reinforced concrete structures with the same lateral-resisting system, i.e. moment resisting frames, in both directions. In detail, Lagaros [17] proposed a procedure for performing multicomponent incremental dynamic analysis (MIDA) by taking into account incident angle. In particular, in accordance with MIDA, a sample of N pairs of record-incident angles was generated through the LHS method. Along this line, Sozonov et al. [27] performed a probabilistic seismic demand analysis that relied on the cloud analysis method; it entailed the selection of a ground motion scenario representative of the Italian territory sorted according to magnitude and distance from the epicentre. The incident angle of the seismic event was deterministically considered with variations between 0 and 180°.

1.2. Scope

Even though numerous studies have dealt with the probabilistic seismic demand of structures subject to seismic loading, a few publications have been devoted to: (i) analyses of representative realistic buildings characterised by different lateral-force resisting systems; (ii) analyses that include input uncertainties, also in terms of earthquake incident angle. All together, they represent basic issues that are explored hereinafter. In detail, the aim of this paper is to provide seismic fragility functions to be used in a full PBEE framework of a 3D steel-concrete composite structure made of a novel type of high-strength steel moment resisting frame in one direction and reinforced concrete shear walls in the other. They were set for the probability of exceeding an