

ΣΧΕΔΙΑΣΜΟΣ ΜΕΤΑΛΛΙΚΩΝ ΚΑΤΑΣΚΕΥΩΝ ΒΑΣΕΙ ΤΗΣ ΓΩΝΙΑ ΕΠΙΒΟΛΗΣ ΤΗΣ ΣΕΙΣΜΙΚΗΣ ΔΥΝΑΜΗΣ

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ΠΕΡΙΛΗΨΗ

Αντικείμενο των μηχανικών είναι ο σχεδιασμός δομικών συστημάτων τα οποία θα ανταποκρίνονται στις απαιτήσεις οικονομικότητας αλλά επίσης θα είναι ικανά να αντέξουν, χωρίς καταστροφικές ζημιές, όλα τα πιθανά φορτία που θα προκύψουν κατά τη διάρκεια της ζωής τους. Ο βέλτιστος σχεδιασμός κατασκευών αποτελεί αριθμητική διαδικασία που δύναται να αντικαταστήσει την παραδοσιακή προσέγγιση σχεδιασμού με μια αυτοματοποιημένη διαδικασία. Στην παρούσα εργασία παρουσιάζεται διαδικασία σχεδιασμού με βάση την επίδοση, η οποία διατυπώνεται ως πρόβλημα βέλτιστου σχεδιασμού κατασκευών, για το σχεδιασμό μεταλλικών κατασκευών με περιορισμούς στις σχετικές μετακινήσεις ορόφων. Ειδικότερα, προτείνεται διαδικασία σχεδιασμού στην οποία λαμβάνεται υπόψη η επιρροή της γωνίας επιβολής της σεισμικής δράσης.

Λέξεις κλειδιά: Σχεδιασμός με βάση την επίδοση; μεταλλικές και σύμμικτες κατασκευές; διεύθυνση σεισμικής δράσης

ΕΥΧΑΡΙΣΤΙΕΣ

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INCIDENT ANGLE BASED DESIGN OF STEEL STRUCTURES

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1. SUMMARY

Engineers always strive to design efficient structural systems which must be as light and economic as possible, yet strong enough to withstand, without catastrophic failures, all possible loads arising during their service life and to absorb the induced seismic energy in a controlled and predictable fashion. Structural design optimization provides a numerical procedure that can replace the traditional design approach with an automated one. A performance-based seismic design procedure is proposed in this work, formulated as a structural design optimization problem, for designing steel and steel-concrete composite buildings subject to interstorey drift limitations. In particular a straightforward design procedure is proposed where the influence on both record and incident angle is considered.

Keywords: Performance-based design; fibre modelling; steel and steel-reinforced concrete composite buildings; incident angle; particle swarm optimization

2. INTRODUCTION

The modern conceptual approach to structural design under seismic loading is based on the principal that a structure should meet performance objectives for a number of hazard levels, ranging from earthquakes of small intensity with small return period, to more destructive events with large return period. This approach constitutes the performance-based design (PBD) concept which has been introduced in order to increase the safety against natural hazards. The current state of practice in performance-based engineering can be found in US guidelines such as ASCE-41 [1], FEMA-445 [2] and ATC-58 [3].

Among others, incremental dynamic analysis (IDA) [4] is considered as an analysis procedure for obtaining good estimates of the structural performance in the case of earthquake hazard and it is considered as an appropriate method to be incorporated into the

optimization procedure. In a recent work by Lagaros [5] multicomponent incremental dynamic analysis (MIDA) has been proposed. Selecting the IDA representative curve in its 3D implementation is not an easy task, since the incident angle selected for applying the two components of the records might influence considerably the product of MIDA.

The objective of this work is the formulation of a performance-based optimum design framework for designing steel moment resisting building structures subject to interstorey drift limitations with reference to their initial cost where the influence of the seismic incident angle is examined by means of MIDA.

3. CRITICAL ORIENTATION OF THE SEISMIC INCIDENCE

A structure subjected to the simultaneous action of two orthogonal horizontal ground accelerations along the directions Ow and Op is illustrated in Figure 1. The orthogonal system $Oxyz$ defines the reference axes of the structure (structural axes). The angle defined with a counter clock wise rotation of the structural axis Ox to coincide with the ground motion axis Ow is called as incident angle of the record.

According to Penzien and Watabe [6] the orthogonal directions of a ground motion can be considered uncorrelated in the principal directions of the structure. In two works by Lopez et al. (2000, 2001) it is proposed an explicit formula, convenient for code applications, in order to calculate the critical value of the structural response to the two principal horizontal components acting along any incident angle with respect to the structural axes.

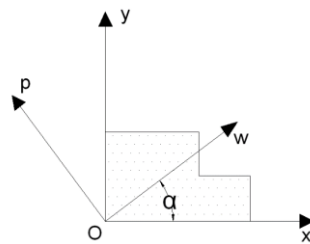


Fig. 1 Definition of the incident angle α

In the work by MacRae and Mattheis [7] it is shown the ability of the 30% SRSS rule and the sum of absolute values methods to assess building drifts for bidirectional shaking effects, while it is also shown that the response is dependent on the reference axes chosen. In the work by Athanatopoulou [8] analytical formulae were developed for determining the critical incident angle and the corresponding maximum value of a response quantity of structures subjected to three seismic correlated components when linear behaviour is considered. Rigato and Medina [9] studied a number of symmetrical and asymmetrical structures where it was examined the influence that the incident angle of the ground motion has on several engineering demand parameters.

4. PERFORMANCE-BASED SEISMIC DESIGN

The modern conceptual approach of seismic structural design is that the structures should meet performance-based objectives for a number of different hazard levels ranging from earthquakes with a small intensity and with a small return period, to more destructive events with large return periods.

		Structural Performance Level		
		Operational	Life safety	Collapse prevention
Earthquake hazard level	50%/50 years (T=72 years)	<i>Standard occupancy facilities</i>	<i>Unacceptable performance</i>	<i>Unacceptable performance</i>
	10%/50 years (T=474 years)	<i>Emergency response facilities</i>	<i>Standard occupancy facilities</i>	<i>Unacceptable performance</i>
	2% in 50 years (T=2475 years)	<i>Safety critical facilities</i>	<i>Emergency response facilities</i>	<i>Standard occupancy facilities</i>

Fig. 2 The design performance objectives for different importance classes

The main part in a performance-based seismic design procedure is the definition of the performance objectives. A performance objective is defined as a given level of performance for a specific hazard level (see Figure 2). In order to assess the structural performance in terms of strength and deformation capacity globally as well as at the element level a nonlinear analysis procedure is required. In this work the PBD framework is based on the nonlinear dynamic procedure (NDP). Three performance levels are considered and seven ground motion records are selected for each hazard level.

5. LOWER BOUND STRUCTURAL DESIGN

The ultimate objective of this study is to compare lower-bound designs, or in other words comparing the designs that satisfy design requirements in the most cost-effective way, i.e. those with minimum cross section dimensions. For this reason, a structural optimization problem is formulated and the designs obtained are then assessed. The formulation of a structural optimization problem is defined as follows:

$$\begin{aligned}
 & \min_{\mathbf{s} \in F} C_{IN}(\mathbf{s}) \\
 & \text{subject to } g_j^{SERV}(\mathbf{s}) \leq 0 \quad j = 1, \dots, m \\
 & \quad \quad \quad g_j^{PBD}(\mathbf{s}) \leq 0 \quad j = 1, \dots, k
 \end{aligned} \tag{1}$$

where \mathbf{s} represents the design vector with the cross-section dimensions of all columns and beams, F is the feasible region where all the serviceability and performance-based constraint functions (g^{SERV} and g^{PBD}) are satisfied, while the objective function considered is the initial cost C_{IN} of the design, which is related to material cost, which includes structural steel, concrete, steel reinforcement, construction labour costs and the cost of the non-structural elements. Additionally, the cost of the contents is included. For the solution of the optimization problem the differential evolution method is employed.

6. NUMERICAL EXAMPLES

In this work, 3D steel moment resisting frame buildings have been considered in order to study the problem of performance-based design optimization of structures. The structures correspond to buildings with two and eight storeys having symmetrical plan view. Figure 3

depicts the plan view and the eight-storey front view of the steel buildings. Steel of class with characteristic yield stress of 235 MPa and modulus of elasticity equal to 210 GPa has been considered. The slab thickness is equal to 12 cm, while in addition to the self-weight of the beams and the slabs, a distributed permanent load of 2.0 kN/m^2 due to floor finishing partitions and an imposed load of 1.5 kN/m^2 , are used. In the numerical test examples section that follows, all analyses have been performed using the OpenSEES [10] platform and each member is modelled with force-based beam-column elements. A bilinear material model with pure kinematic hardening is adopted for the steel fibres, while geometric nonlinearity is explicitly taken into consideration. For the simulation of the bracing members are modelled using an inelastic element with pinned ends [11].

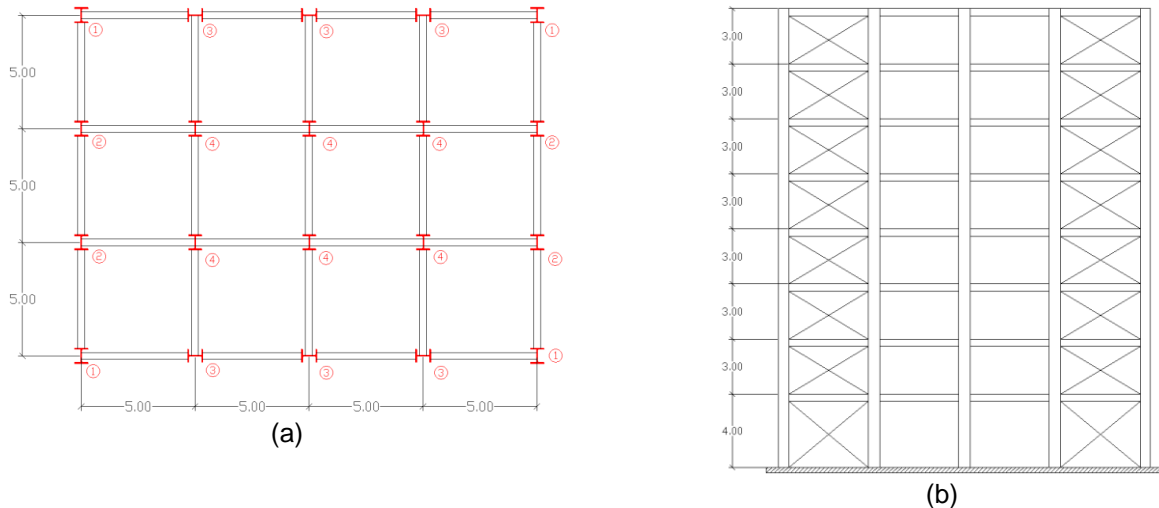
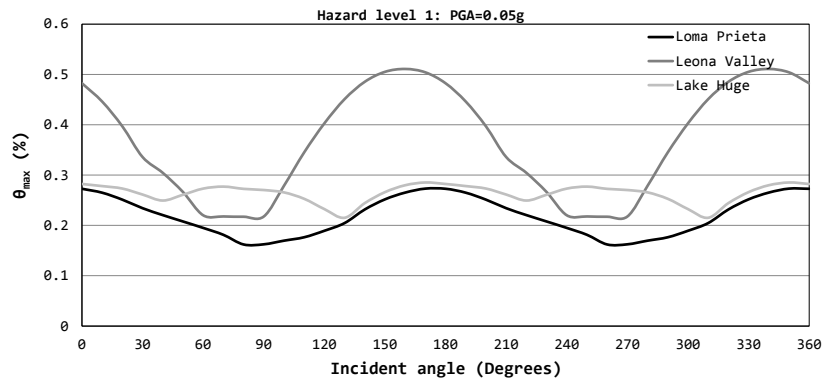


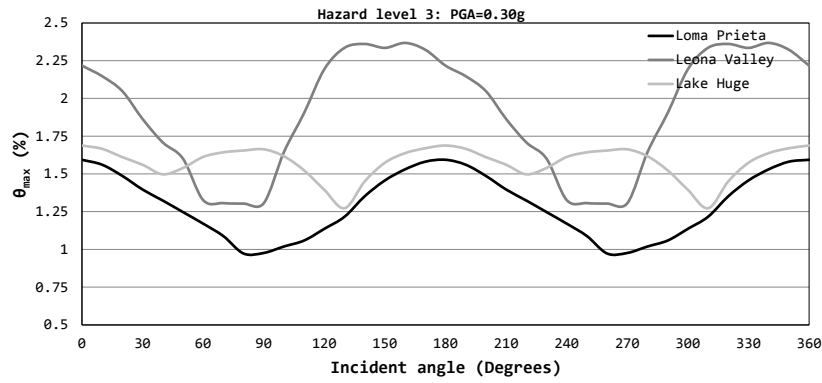
Fig. 3 Test examples - (a) steel building plan view and (b) eight-storey steel building front view

The numerical investigation is composed by two parts. In the first part, in order to examine the influence of the incident angle on the seismic response of the structure, three records have been selected at random and are applied to steel test examples. The three records considered are the Loma Prieta, the Leona Valley and the Lake Hugu. The three records have been applied considering a varying incident angle in the range of 0 to 360 degrees with a step of 5 degrees. In order to examine the influence of the incident angle on the maximum interstorey drift to different intensity levels, the three records have been scaled with respect to the 5% damped spectral acceleration at the structure's first mode period to 0.05g, 0.30g and 0.50g, and the maximum interstorey drift has been recorded for all the incident angles and the intensity levels considered. The variation of the maximum interstorey drift with respect to the incident angle and the intensity level for the three records is depicted in Figure 4 for the two-storey steel test example and in Figure 5 for the eight-storey steel test example. As it can be seen from the seismic response when the incident angle varies in the range of 0 and 180 degrees almost coincides with the seismic response corresponding to incident angle varying in the range of 185 to 360 degrees. This is because the relative ratio of the two horizontal components of the records is close to one, thus the two components are scaled to almost the same intensity level.

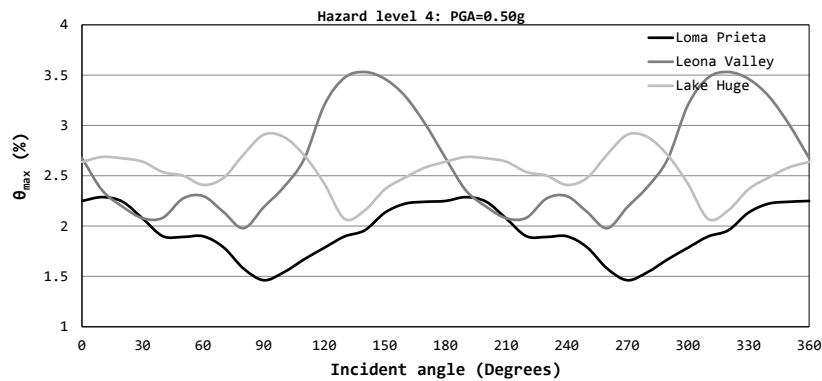
In the second part the structures have been designed based on a PBD optimization framework where the NDP analysis is implemented. The structural elements (columns, beams and bracings) are separated into groups as shown in Figure 3(a). Four groups are defined for the columns one for the beams and one for the bracings. The columns are chosen from a database of 24 HEB sections, the beams are chosen from a database of 18 IPE sections while the bracings are chosen from a database of 50 L sections with equal legs.



(a)



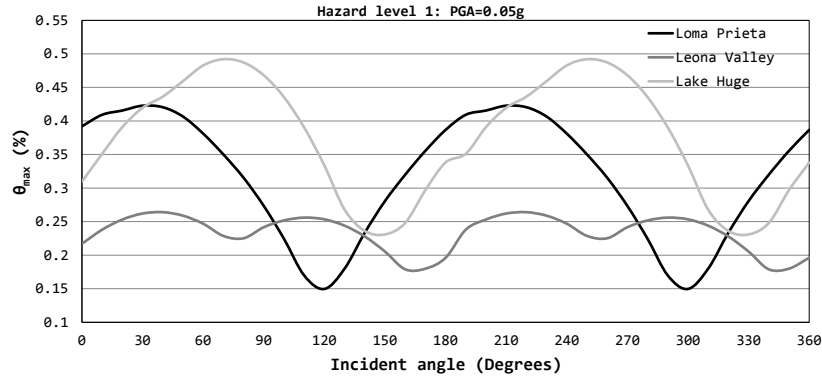
(b)



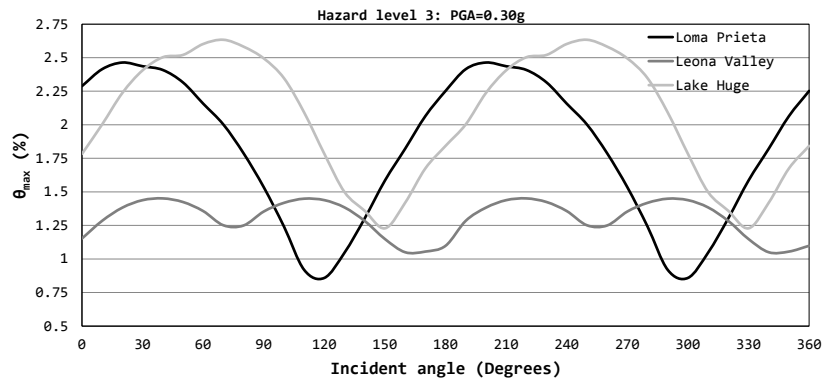
(c)

Fig. 4 Two-storey steel test example-maximum interstorey drift with respect to the incident angle of the record scaled to (a) 0.05g, (b) 0.30g and (c) 0.50g intensity levels

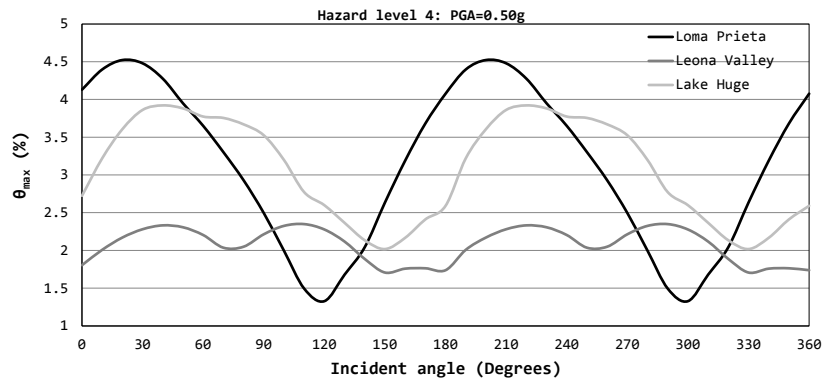
For the purposes of the present investigation six cases (three designs for each type of building) were examined, implementing different design characteristics into the formulation of the optimization problem. In particular, STD1 and STD2 stand for the two-storey steel designs with bracings (4 design variables for the columns, 1 for the beams and 1 for the bracings, 6 in total). SED1 and SED2 stand for the eight-storey steel designs with bracings (4 design variables for the columns, 1 for the beams and 1 for the bracings, 6 in total). STD1 and SED1 are the optimum designs based on the formulation with the Eurocode constraints checks, while STD2 and SED2 are the optimum designs for the critical incident angles obtained from the sensitivity analysis given in Figure 4.



(a)



(b)



(c)

Fig. 5 Eight-storey steel test example-maximum interstorey drift with respect to the incident angle of the record scaled to (a) 0.05g, (b) 0.30g and (c) 0.50g intensity levels

Section	STD1	STD2	SED1	SED2
Group 1	HEB260	HEB100	HEB650	HEB600
Group 2	HEB240	HEB100	HEB340	HEB350
Group 3	HEB320	HEB450	HEB500	HEB500
Group 4	HEB360	HEB600	HEB600	HEB500
Group 5	IPE360	IPE100	IPE550	IPE550
Bracings	L150x115	L90x9	L160x15	L160x15
C_{IN} in €	37,240	62,780	171,924	160,817

Table 1 The two-storey (STD_i) and eight-storey (SED_i) steel building test cases

The optimum cross-sections of the building designs are shown in Tables 1 and 2 along with the initial cost, which is the objective function to be minimised. Comparing the

designs of the two structures, STD_i and SED_i, it is noticed that for the two-storey test example the design STD1 has almost the half initial cost compared to the STD2, while in the case of the eight – storey test example, the SED1 and SED2 are almost the same with the SED2 having the minimum initial cost of the two designs compared.

7. CONCLUDING REMARKS

In the present study, structural design optimization problems for steel building structures are formulated in order to assess the designs obtained for different design procedures. For the needs of this study, 3D steel buildings with regular plan views have been considered. In general optimum designs obtained according to the Eurocodes and for the critical incidence angle are examined. The importance of the critical incident angle considered was presented in a performance based design methodology.

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