16TH EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING THESSALONIKI 18 - 21 JUNE 2018

ANALYSIS-BASED SEISMIC DESIGN FOR GENERALLY IRREGULAR RC FRAME BUILDINGS ACHIEVING MINIMUM TOTAL REINFORCING STEEL WEIGHT

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ABSTRACT

A new analysis-based seismic design method is presented for highly irregular RC frame buildings for bi-directional ground accelerations. Key Engineering Demand Parameters including inter-storey drifts and material strains limits are limited to target values. This is achieved while simultaneously minimizing total steel volume. This results in economic design solutions experiencing reduced peak base shears and over-turning moments. The methodology relies solely on analysis tools. No knowledge of structural optimization is necessary. The method presented typically requires only a few iterations for convergence. This analysis-redesign approach is therefore quite suitable for practical use.

Keywords: RC frame structures; optimal design; Performance-Based-Design; analysis-redesign; fully-stressed-design.

1. INTRODUCTION

Due to their alleged aesthetic appeal, irregular buildings are popular among many builder designers and owners. However, seismic vulnerability also correlates relatively well with structural irregularity (Stathopoulos and Anagnostopoulos, 2005; Kyrkos and Anagnostopoulos, 2011). Seismic response of irregular structures is harder to predict by simplified analyses (Moehle and Alarcon, 1986; Valmundson and Nau, 1997; Anagnostopoulos and Kyrkos, 2015). For this reason, advanced analysis and modelling is often required for response prediction of this class of structure. Having powerful analysis tools available for verification is an advantage. However, there is a serious need for simple robust design methods for highly irregular buildings. Ideally, such methods would produce economic designs that reliably achieve the target performance levels.

This paper presents a simple iterative procedure for seismic design of 3D irregular RC frame buildings, as proposed by the authors (Lavan and Wilkinson, 2016). It is based a two step iterative approach. In the step one, a trial design is analyzed. In step two, flexural strengths and rigidities are redesigned based on a comparison of the step one analysis results and the target performance levels. These two steps are repeated until convergence, which is usually obtained within 10 to 20 iterations. The approach produces designs that are as economic as possible while complying with limits on inter-storey drifts and strains (or local ductilities). Due to the procedure's transparency and simplicity, it is likely to be useful for both the research and practicing communities.

2. PROBLEM STATEMENT

Structural design of RC frames is specified in terms of cross section dimensions and steel reinforcing content: location and amount. In regions of low seismicity, gravity and wind considerations often govern

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the design. In significantly seismic regions, these considerations provide minimum initial flexural strength and stiffness requirements. Deviation from the initial cross section dimensions is only required when the seismic target performance levels cannot be achieved even for maximum or minimum reinforcing steel ratios. The reinforcing steel ratios are the primary design variable and the cross section dimensions are secondary design variables.

Construction cost is significantly affected by the total weight of reinforcing steel. A minimum value of this parameter is therefore targeted. Seismic performance levels are defined in terms of inter-storey drift and local ductilities. These parameters also correlate well inversely to total steel weight. This is expected considering that flexural strength and rigidity are directly proportional to steel area. Peak force response including base shears and overturning moments also reduce with total steel weight producing additional cost savings from smaller foundations. Peak total accelerations also diminish (see e.g. Lavan, 2015). This reduces damage to acceleration sensitive building contents. Therefore, total steel weight (expressed by the sum of seismic element flexural strengths) is minimized.

The minimum total steel reinforcing is governed either by gravity or wind considerations or minimum steel reinforcing ratios or by the target seismic performance levels: if the steel reinforcing area is too low, flexural strength and rigidity will not be high enough to limit peak inter-storey drifts and local ductilities to the selected performance levels. Different limits are set for each limit state/seismic intensities.

In the following section, we first present the model considered for the definition of the damper-brace behavior and the relative equations. Then, we recall the equations of motion for a structure with nonlinear behavior and equipped with nonlinear fluid viscous dampers, and subject to a realistic ground motion acceleration.

3. PROPOSED METHODOLOGY

The proposed methodology relies on an optimality criterion of the Fully-Stressed-Design (FSD) type. The earliest FSD type optimality criterion was proposed by Cilley (1900). Cilley also proved it to lead to a formal optimum for the design of the truss of minimum weight under stress constraints. It was shown that, for this problem, in the optimal design all bars reach the allowable stress in at least one loading condition. Accompanied to the FSD optimality criterion is the Analysis/Redesign (AR) algorithm where the engineer performs an analysis to a given design and modifies the cross sections of the bars accordingly. Here, if the stress in the bar is lower than the allowable, the engineer would decrease the bar cross section. Contrarily, if the stress in the bar is larger than the allowable, the engineer would increase the bar cross section. Convergence is usually obtained within a few iterations.

Characteristics of the FSD type have also been identified in optimal designs of seismic retrofitting of buildings using viscous dampers (Lavan and Levy, 2006, 2010). The total added damping was to be minimized while inter-storey drifts were constrained to allowable values. These optimality criteria were further accompanied by an AR type optimal design scheme (Lavan and Levy, 2005, 2009; Levy and Lavan, 2006). Such design schemes were also proposed in other problems based on intuitive FSD type criteria (Lavan and Daniel, 2013; Daniel and Lavan, 2015; Lavan, 2015). Comparison of the obtained designs using these methods with those obtained using formal optimization tools (Daniel and Lavan, 2014; Lavan and Dargush, 2009) revealed that, if not optimal, they are at least near optimal. An AR type algorithm has also been adopted for the seismic design of plane RC frames (Hajirasouliha et al., 2012). In their problem, minimized total steel volume was targeted whole limits were assigned to deformations along the height of the building.

In view of the above experience, and the strong relation between the inter-storey drift of a given storey and the strength and stiffness of the same storey, it is expected that an optimized design for the problem stated in the previous section would possess the following intuitive optimality criterion:

For 3D framed structures, the optimal design will attain a flexural strength in beams of peripheral frames, larger than the minimum allowed, only in floors for which the performance measure has reached the allowable.

The performance measure is taken here as the maximum of the normalized (by its allowable value) inter-storey drift of the peripheral frame in the storey below the floor, and the maximum of the normalized (by their allowable values) ductility demands of all beams in that bent. For the first floor, the maximum of the normalized (by their allowable values) ductility demands of all column bases of that peripheral frame is also taken.

In view of the discussion above, only peripheral frames are considered as lateral load resisting systems. Inner frames are considered as gravity frames and their beams and columns are designed for gravity loads only, while detailed for ductilities congruent with the expected peak deformations. If the use of peripheral frames only does not lead to a feasible design, inner frames are gradually added as lateral load resisting systems.

The proposed scheme is described in Figure 1. Where $M_{yb}^{(p+1)}$ and $M_{yb}^{(p)}$ are the nominal flexural yield strengths of seismic beam b for iterations $p+1$ and p respectively. $PI_{\theta j}^{(p)}$ and $PI_{\mu b}^{(p)}$ are the parameters $PI_{\theta j}$ and $PI_{\mu b}$ defined in section "Optimization problem" computed for iteration p, respectively. For more details, the reader is referred to (Lavan and Wilkinson, 2016).

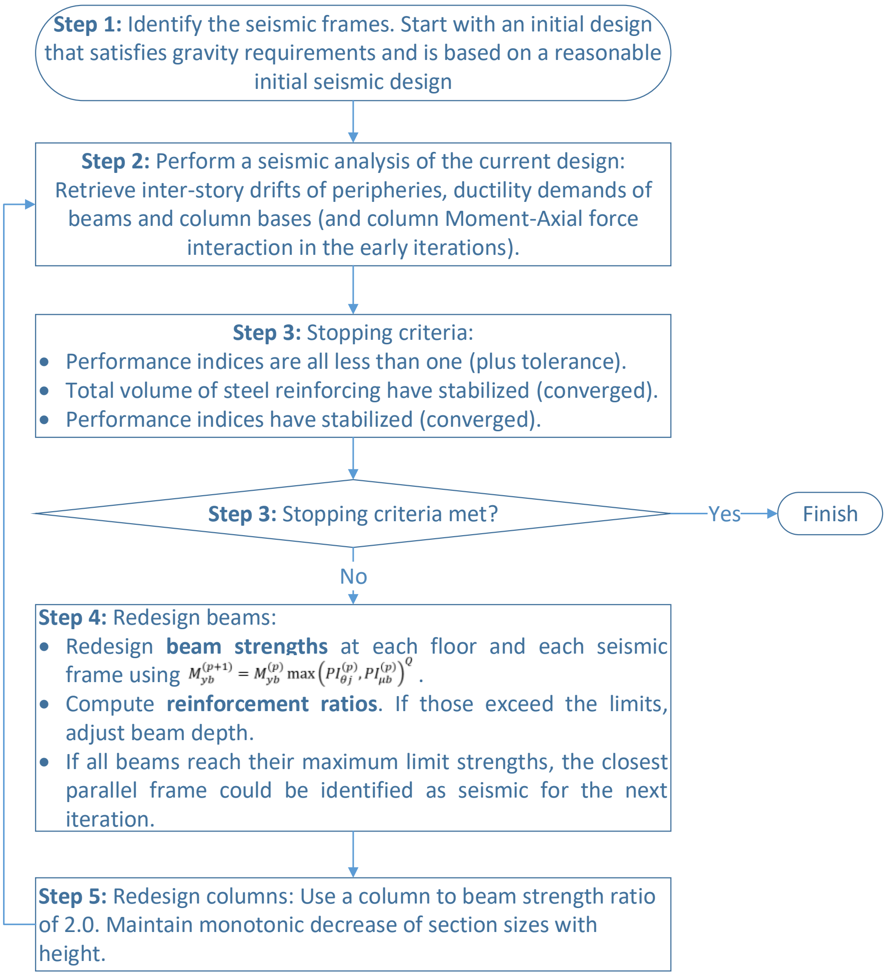

Figure 1 Proposed design scheme

4. NUMERICAL EXAMPLE

This example adopts the generally irregular 6 storey RC frame structure shown in Figure 2. The design was performed for two limit states: a serviceability limit state and a life safety limit state. For the serviceability limit state, column bases and beams were assigned with an allowable of ductility of 5 while inter-storey drifts were limited to 1% of the storey height. For the life safety limit state the allowable ductility was set to 7.3 while 2% inter-storey drifts were allowed.

Five sets of two horizontal components of ground motions were selected from the LA10/50 set Somerville et al. (1997) and were modified using the program SeismoMatch (Seismosoft, 2010) to match the design response spectrum. The analysis of the building was performed using Ruaumoko (Carr, 2006).

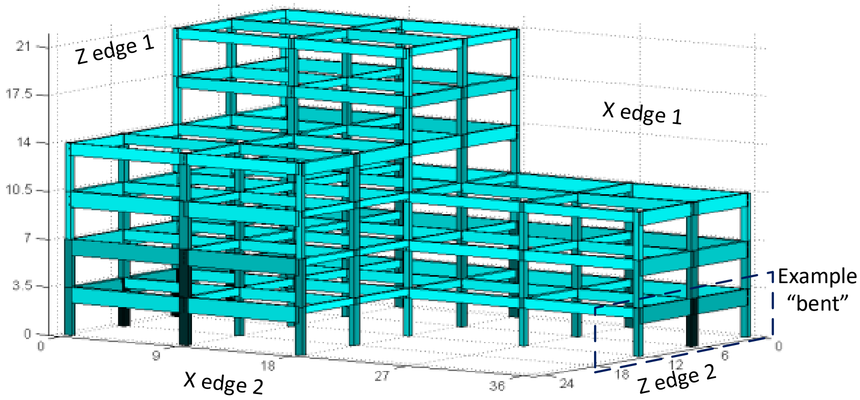

Figure 2 Six storey generally irregular RC frame structure.

Figure 3 presents the Maximum Constraint Violation (MCV) and the Objective Function (OF) value as a function of the iteration count. As can be seen, 20 iterations were required for full convergence. However, an acceptable MCV < 10% was achieved in approximately 10 iterations.

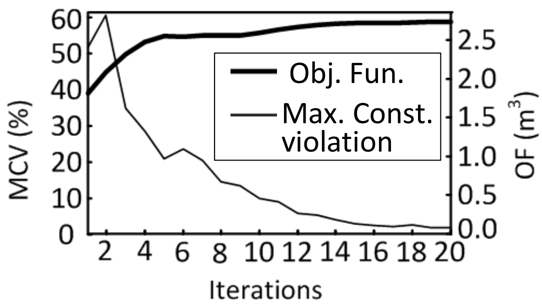

Figure 2 Maximum Constraint Violation and Objective Function value as a function of the iteration count

The behaviour of the final design in terms of inter-storey drifts and ductility demands for are presented in Figure 4.

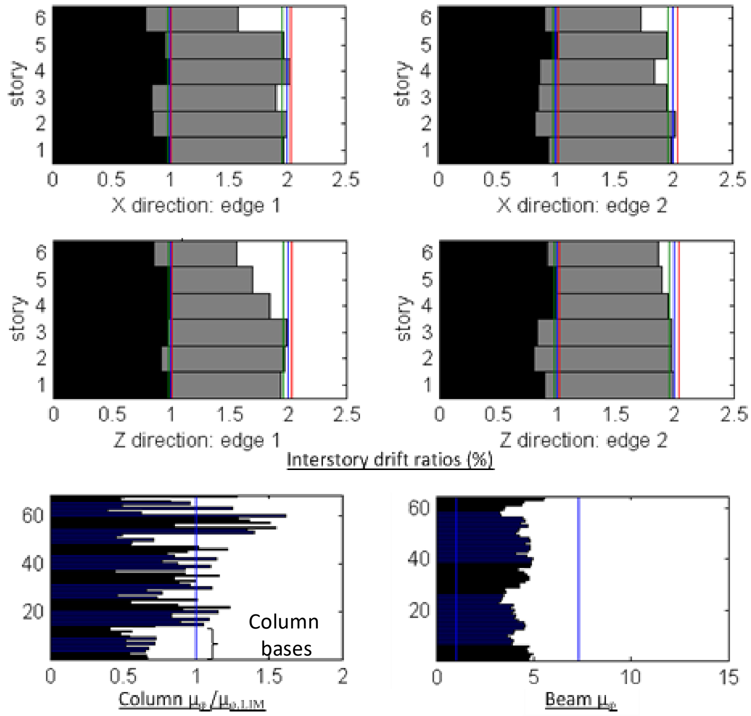

Figure 3 Analysis-Redesign Design Verification results (The black drift bars show the serviceability mean peak demands and the grey bars the ULS demands).

As can be seen, most stories of most peripheral frames reached the allowable inter-storey drifts in at least one limit state. Otherwise, they were at their minimum strength. Ductility demands of the beams and column bases were well within their allowable limits. Some limited plasticity in the columns above their bases was apparent. This performance was very satisfying for such a highly irregular structure.

5. CONCLUSIONS

An analysis-based seismic design method was presented that produces relatively economic solutions for 3D generally irregular frame structures that reliably achieve the target seismic performance levels. The approach minimizes the total moment capacity of all members, while satisfying inter-storey drift and ductility demand constraints as well as section size limits and practical reinforcing steel ratio limits. As the methodology is straight forward and intuitive, and requires analysis tools only, it is suitable for practical use in design offices.

The methodology was applied to a 6 storey setback structure to demonstrate its utility. Practical convergence to within 10% of the final design was achieved with 10 iterations, which is manageable even though nonlinear time-history analyses are adopted. This further highlights the applicability of the method to design offices. As intended, the final designs attained flexural strengths larger than the minimum initial values, only in floors for which the engineering demand parameters otherwise would have exceeded the selected limits. Thus, strength was assigned only where necessary for achieving the selected target performance levels.

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