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SOIL-STRUCTURE INTERACTION EFFECTS ON THE SEISMIC BEHAVIOUR OF A RC DUAL WALL-FRAME BUILDING

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Abstract

Structural analysis has traditionally been carried out with the assumption that the structure is rigidly fixed at its base. Explicit consideration of soil-structure interaction (SSI) effects has been limited to only special cases where the scope or importance of the structure was considered significant enough to warrant the additional analysis effort. On the other hand, if SSI effects indicate a reduction of structural responses, no effort is generally given for further optimization of the seismic design. Determining which cases warrant the additional effort and scrutiny has not been well established. The aim of this work is to study the influence of SSI on the seismic behaviour of structures with systems consisting of both walls and frames, namely, dual wall-frame structures. To do so, a nine-story RC dual wall-frame building structure founded on isolated footings was considered as a study case. The outcomes from this study indicate that the consideration of SSI in structural analysis of dual wall-frame buildings tends to change the distribution of base shear force and, therefore, it may change the classification of the structural system which is directly related to the estimation of seismic forces.

Keywords: Soil-Structure Interaction, dual wall-frame building, flexible-base building, non-linear static analysis.

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1 INTRODUCTION

Unlike the traditional design, where the structure is considered to be fully fixed at its base, Soil-Structure Interaction takes into account the interconnection and the interaction between the structure, the foundation and the soil beneath. As such, rightly so, this phenomenon is often known as soil-foundation-structure interaction.

In recent years, a lot of work has been dedicated to the soil-structure interaction, with frame systems being among the most investigated structural systems. On the other hand, the influence of soil-structure interaction in the structures consisting of mixed structural systems such as dual systems, is not as extensively studied as in frame systems [1]. However, some notable studies examine SSI in dual systems. For example, Carbonari et al. investigated both linear and nonlinear response of dual systems resting on pile foundations with consideration of soil flexibility [2,3], Nechevska-Cvetanovska, et al. studied the role of SSI on a dual system where only the walls are engaged in resisting lateral forces [4], Emami and Halabian conducted an investigation on dual systems, relating ductility demand to foundation flexibility [5], etc. However, a lot of work is yet to be done to fully understand the influence of soil-structure interaction on dual systems.

In this work, the effects of soil-structure interaction on the seismic response of a dual wall-frame building structre are investigated. To do so, a hypothetical 9-story reinforced concrete structure was considered. For the considered building, first the elastic analysis was carried out in order to design the structural members. The structure was designed in accordance with EN 1998-1 [6]. For elastic analysis, the building was considered to be fixed at its base. Then, having the already designed fixed-base building with provided reinforcement contents, a new (flexible-base) model was created so that the supports of the fixed-base building were substituted with springs. Next, for both models, key design quantities – base shear, displacement shapes and interstorey drifts - were examined and the nonlinear static analysis procedures were employed to assess their performances. At the end, the results of the flexible-base building were compared with those of the fixed-base building to highlight the effect of SSI in the dual wall-frame building.

2 CASE STUDY

2.1 Building description

A nine story RC dual wall-frame building structure represented through the three-dimensional model (Figure 1) constructed in Robot Structural Analysis Professional 2024 [7] was considered as a study case in this work. In order to isolate torsional and nonregularity effects, a regular and symmetrical configuration was chosen for the building. This way, the walls with 30cm in thickness and with a 2.5m in length are concentrated at each corner of the building. The member cross-sections dimensions (in cm) are shown in the figure. Beam and columns were modelled with frame elements, whereas walls and slabs were modelled with shell elements. The height of each story is equal to 3m, giving a total building height of 27m. The building has four bays in X-direction and three bays in Y-directions. Each bay has a length of 6m. The foundation system of the building consists of spread footings interconnected with tie beams. The depth of spread footings is 1.2m.

2.2 Design considerations

Since the building consists of both walls and frames, it is classified as dual system. However, dual systems are not equally classified in all building codes. For example, according to ASCE/SEI 7-16, the systems are classified as dual if the contribution of each system in resisting base shear is not less than 25%, which means that up to 75% of the base shear must be resisted by the other system [8]. On the other hand, in EN 1998-1 the range of dual system classification is narrower (35% to 65%). In addition, dual systems are classified as frame-equivalent dual systems or wall-equivalent dual systems, depending on which system resists the larger percentage of base shear. Since the wall contribution in resisting base shear is about 64%, the building is classified as wall-equivalent dual system. It is worth noting that the moments of inertia for walls, columns and beams were reduced by 50% to account for cracking of the elements.

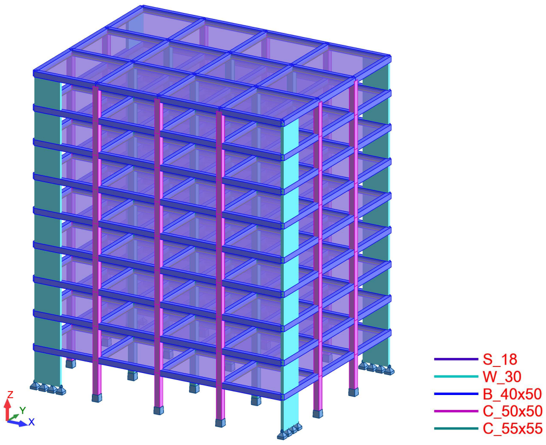

Figure 1: 3D view of the fixed-base model of the building

The building was designed in accordance with EN 1998-1 provisions for a location with a peak ground acceleration of 0.3g. Type 1 design spectrum was used, corresponding to soil category C and a behaviour factor of 3.6 (wall-equivalent dual system and medium class of ductility (DCM)). The material grades used are: C25/30 for concrete and B500B for reinforcing steel.

2.3 Soil-Structure Interaction (SSI) modelling

There are approaches for Soil-Structure Interaction modelling: the direct approach and the substructure approach. In the direct approach, the structure, its foundation and the soil are all modelled as a continuum using the finite elements. This approach provides higher accuracy but requires significant computational time and effort. On the other hand, the substructure approach analyses the structure and the soil separately, where impedance coefficients are estimated first and then incorporated into the mathematical model using springs and dashpots. This simplification makes this approach easier to apply and computationally more efficient. In this work, the substructure approach was used for SSI modelling, where the soil and the foundation flexibilities are represented through the Beam on Nonlinear Winkler Foundation (BNWF) modelling. The spring values were calculated using the equations derived by Pais and Kausel [9].

2.4 Building performance

The seismic performance of the considered building was estimated using the N2-method developed by [10]. The nonlinear static procedure was performed in SAP 2000 [11] , where the expected material strengths were used. The ends of the members are expected to undergo nonlinear behaviour. So, plastic hinges were assigned to these regions. Outside these regions, the members were modelled elastically. The definition of the hinge properties was done automatically by the software based on tables of ASCE 41-13 [12].

3 RESULTS AND DISCUSSION

The results from both elastic and nonlinear analysis are presented in this section. Since the building has shown very similar behaviour in both orthogonal directions, only the results for its X-direction are shown here. The results corresponding to the fixed-base model will be denoted as *Fixed*, whereas those corresponding to the flexible-base model will be denoted as *Flexible*.

3.1 Base Shear

The following table shows the base shear forces resulting from elastic analysis. A slight reduction (about 2%) of base shear is noticed as the base of the model changes from fixed to flexible. At first, it seems that the incorporation of SSI in the mathematical model does not have any significant effect on base shear. However, when analysing the contributions of walls and frames in resisting base shear in both fixed-base and flexible-base models, a significant discrepancy is observed. The discrepancy arises from the considerable difference in stiffness between the walls and the frames. Since walls are much stiffer than frames or columns, they are far more sensitive to base softening compared to frames or columns. Although walls are more sensitive to base softening than frames, they do not experience any increase in base shear. On the contrary, their base shear decreases. In fact, a redistribution of forces occurs, with the fraction of base shear deducted from the walls being transferred to the frames. Therefore, it can be said that the walls are more sensitive to SSI, but the frames are more affected by it.

Quantity	Fixed	Flexible
Overall Base Shear (kN)	3816	3729
Base Shear in Walls (%)	63.76	41.75
Base Shear in Columns (%)	36.24	58.25

Table 1: Base shear forces in fixed-base and flexible-base models.

The redistribution of base shear does not affect only the building components, but also the overall behaviour of the building. Recalling that the classification of dual wall-frame systems depends on the distribution of base shear between walls and frames, it is evident that this redistribution alters the system classification. Specifically, in the fixed-base case the system is classified as a wall-equivalent dual system, whereas in the flexible-base case the system is classified as a frame-equivalent dual system. A similar distribution of base shear was observed in the pushover analysis.

3.2 Displacements and interstorey drifts

The displacement shapes and the interstorey drifts of both the fixed-base and flexible-base models, as obtained from elastic analysis, are shown in Figure 2. Note that these quantities were scaled by the value of behaviour factor (3.6) as required by EN 1998-1.

From Figure 2 (left), a slight increase of the displacements along the entire height of the building is observed when the SSI is considered. In general, the increase in displacements for the flexible-base case appears to be uniform. However, at the base of the building, the displacement shape of the fixed-base model exhibits a more cantilever-like form, whereas in the flexible-base case this cantilever-like behaviour is softened.

The interstorey drifts for both building models are shown on the right-hand side of Figure 2. Generally, from the fourth storey to the top, no noticeable difference is observed between the two models. However, in the first three stories, a significant increase in interstorey drift occurs when SSI is considered. Despite this increase, the interstorey drifts remain smaller than the maximum interstorey drift of the fixed-base model, except at the third storey, where a slight exceedance is observed.

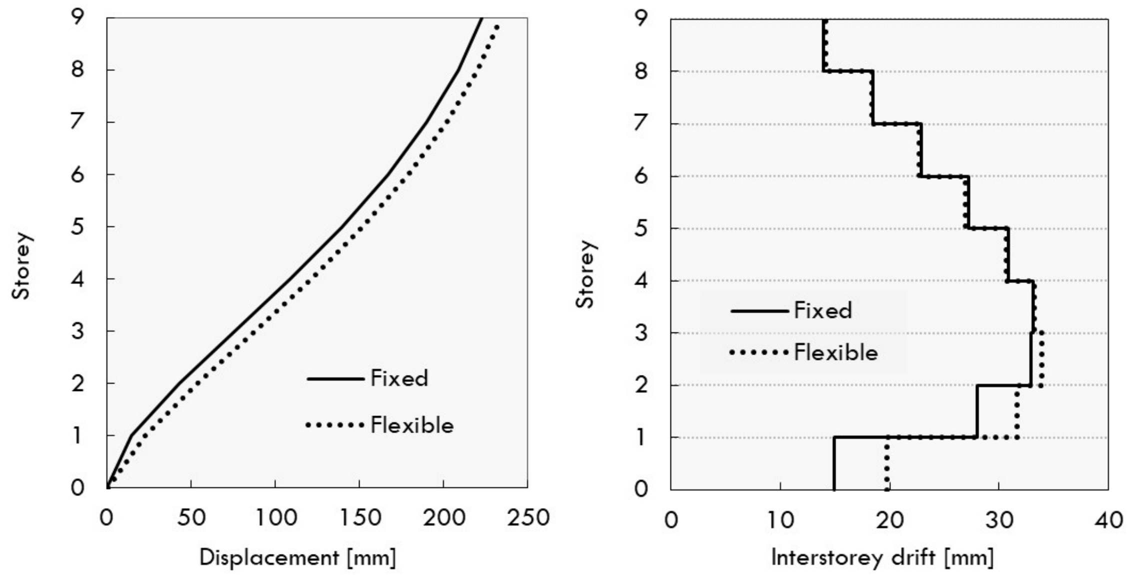

Figure 2: Displacement shapes (left) and interstorey drifts (right) for both the fixed-base and the flexible-base models

3.3 Performance assessment

The performance assessment for both the fixed-base and flexible-base models was conducted to evaluate their behavioural differences beyond the elastic range. To do so, first the nonlinear static analysis was carried out to obtain the capacity curves. Then, both the response spectra and the capacity curves were transformed into ADRS format for direct comparison.

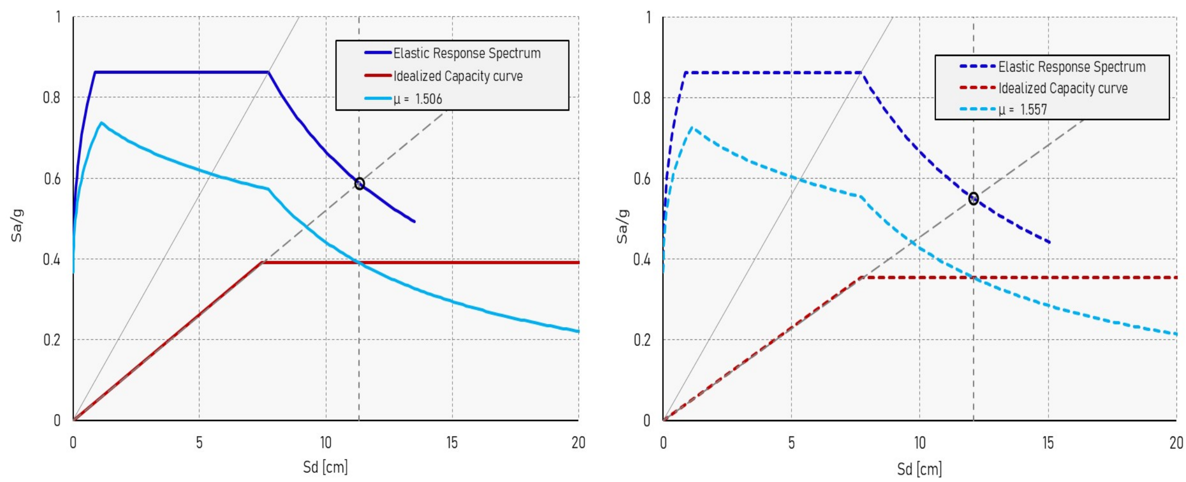

Figure 3: Performance assessment for fixed-base model (left) and the flexible-base model (right)

Figure 3 shows that both models exhibit a very similar performance. The flexible-base model experiences a slight decrease in strength and a slight increase in deformation compared to the fixed-base model. In general, SSI does not substantially affect the structure's performance assessment.

4 CONCLUSIONS

The Soil-Structure Interaction effects on a nine-story RC dual wall-frame structure designed in accordance with EN 1998-1 have been investigated in this paper. From this study, the following conclusions can be drawn:

- SSI significantly redistributes the forces in dual systems to the extent that it may change the classification of the system from wall-equivalent dual system to frame-equivalent dual system.
- The deformations are increased along the entire height of the building when SSI is considered. Also, SSI softens the cantilever-like form of the deformation shape.
- In the stories near the base of the building (the three stories from the base), interstorey drifts significantly increased when the soil flexibility was taken into account. No significant change of the interstorey drift is noticed in the stories above.
- A nonlinear performance assessment showed a slight reduction in stiffness and a slight increase in deformations for the flexible-base model, relative to the fixed-base model.

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