Improving Seismic Structural Performance of an Underdesigned R. C. Building

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SUMMARY:
The present paper presents numerical studies done on a real building structure, built in the early 1950's in a hazardous seismic area of South Europe, for which during the latest years some significant design errors have been identified. This reinforced concrete RC structure has been studied within the European project Seismic Performance Assessment and Rehabilitation of Existing Buildings, SPEAR, in order to improve its performance to seismic loading for these classes of structures. It was performed a finite element modelling and analysis FEA, based on dynamic time-history simulations in nonlinear domain in order to point out the effects of rehabilitation process. The numerical investigations in time domain have considered the Montenegro '79 Herceg-Novi and Romania Vrancea 1977 records in order to evaluate the effects of these seismic actions for this class of under - designed structures and providing a inexpensive way of evaluating structural behaviour under dynamic loads.

Keywords: Structural rehabilitation, Reinforced Concrete, Time-History Analysis

1. INTRODUCTION

It is known that the existing building stock is mostly represented by old buildings which have exceeded their life stage. On the other hand these buildings have been constructed using old design norms and regulations which do not fulfil today's structural performance criteria. Considering also the latest up rise in the engineering research industry and the changes that take part in the design procedures stated in the new design norms, we see that most of the built environment cannot meet the safety quality criteria. These issues are most worrying especially in the seismic active areas, due to the fact that anti-seismic design norms have been developed only recently in the last decades. It is considered that the problem of under designed buildings will solve itself gradually by developing new urbanistic projects. However, economically speaking, the process of structural rehabilitation of existing structure isn't considered a totally feasible choice, with the exception of high interest buildings, such as administrative buildings, hospitals, critical post-earthquake structures.

In order to asses structural performance of old buildings, form a technical point of view more challenges arise from local conditions and the inability to implement new architectural and design concepts to previous constructions. This job is even more difficult for the earthquake engineers worldwide, which have to make sure that the built environment doesn't pose threat to the population or to the inhabitants of these aging constructions. From technical point of view, the problem of assessment and retrofitting of old buildings is more difficult than that of seismic design of new ones and has only recently been addressed by earthquake engineers worldwide. There are also situations when the lack of precise information leads to very high costs in rehabilitation process when dealing with particular cases of damaged old buildings. The rehabilitation processes of most old under designed buildings doesn't follow strict rehabilitation criteria, therefore leaving engineers to estimate roughly the main steps in the process. The feasibility of these decisions is directly deviated in the total costs of the rehabilitation process, which are very often very high. In recognition of the importance of the domain of structural rehabilitation there were developed the first standards for structural upgrading which address the subject of seismic rehabilitation of buildings, (Fardis, 2005). The standard which addresses these issues is Part 3 of Eurocode 8 “Assessment and Retrofitting of Buildings”. Romanian standards also address the issue of structural rehabilitation in the 3rd Part of Romanian Seismic regulation P100-2008 “Cod de Proiectare Seismică - Prevederi Pentru Evaluarea Seismică a Clădirilor Existente”, (P 100, 2008).

In order to design and study the behaviour of reinforced concrete (R/C) buildings in high seismicity areas, one usually follows the capacity design procedure, and uses tools such as modal analysis and non-linear time-history analysis to reveal it’s behaviour to dynamic seismic motions, (Mazars, 2005).

2. DESCRIPTION OF R.C. MODEL

The structure chosen for numerical experiments is a reinforced concrete (R.C.) three level building, built specifically after old European design codes. These design codes did not include in the design procedure, seismic design procedures. The main design provisions in old building codes only took into account gravity loads, (Ile, 2005), which raises many problems in most old buildings constructed in seismic areas.

The structure evaluated in the present paper was extensively studied within the research program: European Seismic Performance Assessment and Rehabilitation of Existing Buildings (SPEAR), and with this occasion there were conducted a series of seismic tests on seismic platforms around the world.

The structure is mainly characterized by plane horizontal irregularity, with three levels of equal height of 3m. The in-plane irregularity is developed in both directions, X&Y, with frame openings of 3 m up to 6 m, as represented in Figure 2.1.The slabs thickness is of 15 cm for each floor. The slabs are reinforced with smooth bars 8 mm in diameter, as the old design codes stated, with 100 mm up to 400 mm spacing between bars. The same reinforcing plan is applied for the beams and columns at each of the three levels of the structure. The transversal sections of the beams are 250 mm wide and 500 mm deep. The columns have square transverse section of 250/250 mm except for column C6 which is of lamellar shape and its cross-section is 250 mm wide and 750 mm deep. The longitudinal reinforcement for the columns is represented by 12 mm diameter bars. The spacing of the stirrups both in the columns and in the beams is of 250 mm, equal to the transverse cross-section of the column.

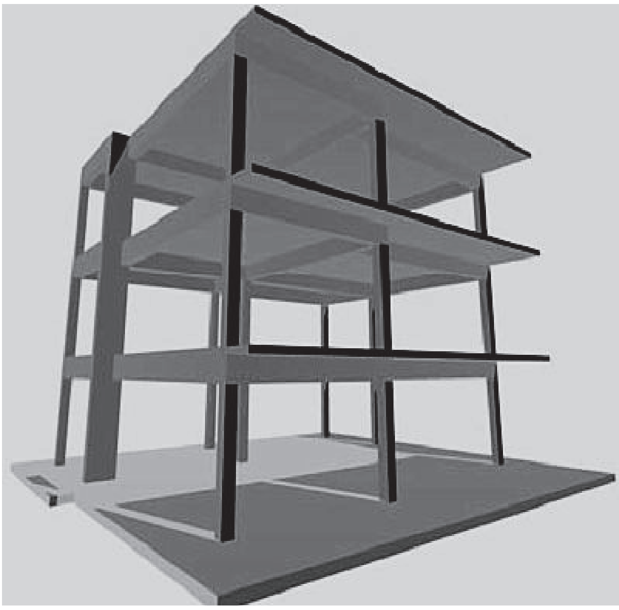
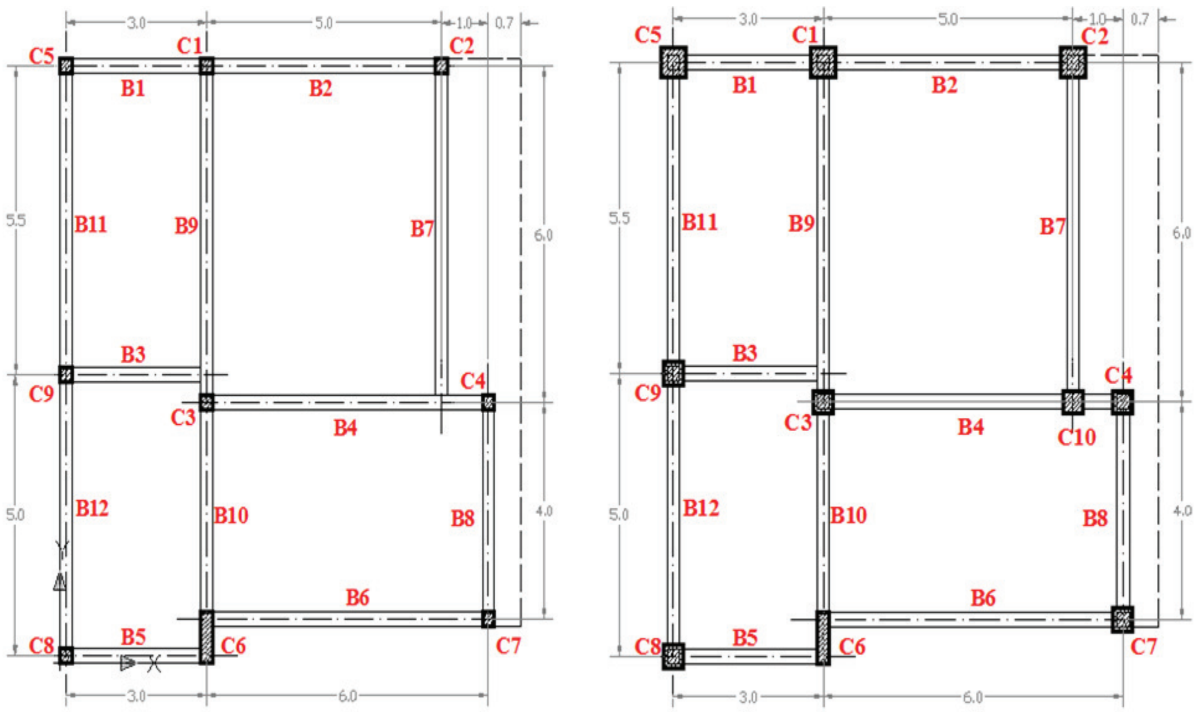


Figure 2.1. The SPEAR structure, (Mola, 2005).

Considering all these characteristics, we can assign the SPEAR structure to a special class of structures: multi-level regularly asymmetric structures. The main characteristic of this class of structures is represented by the fact that its mass centre (MC), strength centre (SC) and rigidity centre (RC) of each level are all situated on a different vertical axis, separated by a local eccentricity, (Mola, 2005).

2.1 Structural Rehabilitation Process

The weakest points of the building are represented by the structural joints, respectively the link between the beams and the columns, since the stirrups don't have continuity in these critical areas. The structural elements , in their original configuration , offer very little ductility. Thus, the purpose of the paper is to provide a structural rehabilitation process in order to reduce the impact of the torsional effects which is greatly felt in the structural response, and to improve lateral rigidity of the building. This is done by repositioning the mass centre and the strength centre on each level, without specifically following the relocation of the rigidity centre, (Mola, 2005). Previous studies have shown that in inelastic domain, the structural response caused by torsion is mainly governed by structural strength and not by the eccentricity of structural rigidity, (Rutenberg, 2002).
Another serious design error is represented by the direct intersection of the beams adjacent to columns C3 and C4, as displayed in Figure 2.2 (a) resulting in beam-on-beam hinges without any support on a column.



(a) (b)

Figure 2.2. The structure geometry of: (a) initial building, (b) retrofitted building.

Due to the bad design of the structure, it was proposed a rehabilitation solution, as represented in Figure2.2(b) in order to correct the design flaws as much as possible. The main problem is represented by the under designed columns and overdesigned beams, which inevitably leads to the formation of the plastic hinges in the columns, even in early stages of lateral loading.
This was solved by jacketing the existing columns with a new layer of reinforcement and increasing the transversal cross-section form 250/250 mm^2 to 400x400 mm^2, and for the columns C1, C2 and C5 respectively to 500x500 mm^2. It was also addressed the issue of improper beam-on-beam intersection by constructing a new exterior column, where the two beams intersects.

3. STRUCTURAL MODEL

There were developed two analysis models. One of them represents the original structural geometry and characteristics, and the second representing the rehabilitated structure of the studied model.
For both cases there were conducted modal analyses, as well as dynamic time-history analyses. The comparison of the results was done in order to evaluate the structure as a representative rehabilitation model. In order to compute the aforementioned analyses it was used the structural analysis software SAP2000 vs. 14.2.4, (CSI, 2010). Within the structural analysis software there were defined precise models of the materials used in the considered structure, in order to apply these proprieties to the two computational models.

The structural analysis model used in SAP2000 is composed of linear frame type elements for columns and beams, and shell surface elements as represented in Figure 3.1. The models are comprised of 4758 shell finite element (FE) and respectively 60 frame FE. The loads applied on the structure are defined by variable or constant forces, displacements and accelerations.

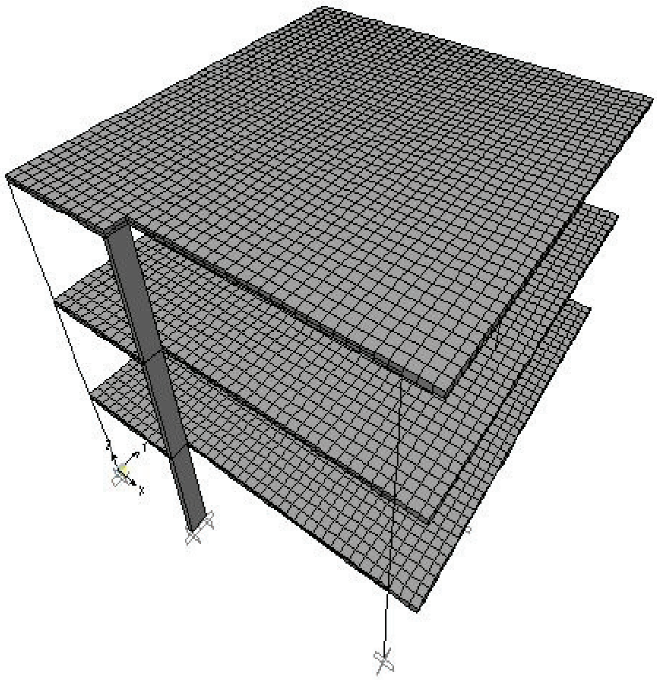


Figure 3.1. FE Analysis model of the SPEAR structure.

Considering the fact that the beams adjacent to column C6 are not aligned, column C6 was modelled using a shell-type equivalent structure, with equivalent reinforcement area in order to ensure proper connections with the ends of the adjacent beams.

4. RESULTS

There were computed comparative values for the modal analysis, push-over analysis and dynamic time-history analysis in order to evaluate the effects of the rehabilitation process. For the dynamic time history analysis there were considered two types of accelerograms, specific for Montenegro, from Herceg Novi area and for Romania from Vrancea area. These accelerograms have different frequency content and therefore the structure will be excited differently, both by a shallow surface earthquake and a deep surface earthquake. The comparative structural response is evaluated accordingly.

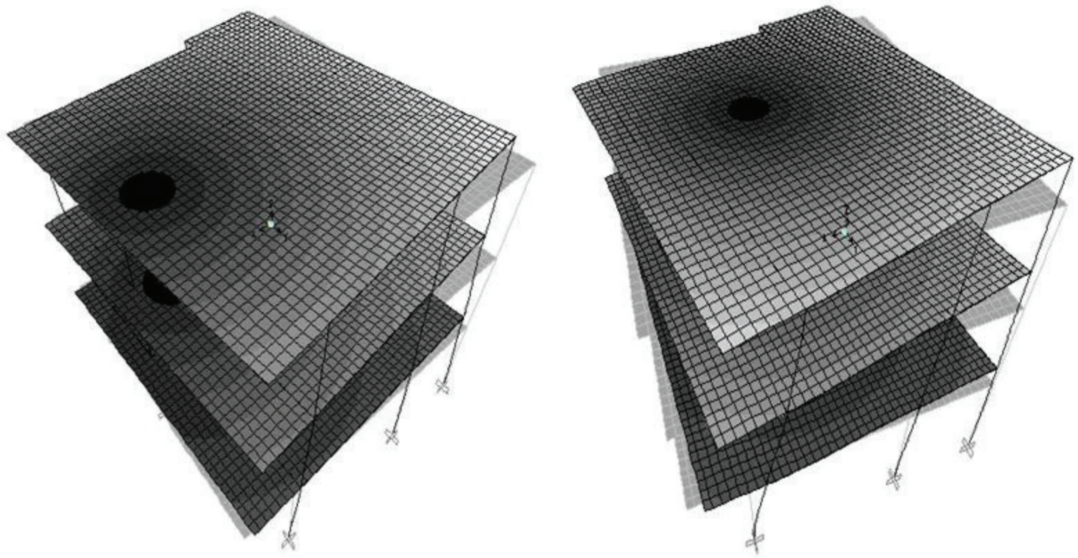
4.1. Comparative Modal Analysis Results

The frequencies and the mode shapes for both structural models are consistent, corresponding to the research of the S.P.E.A.R International Workshop Project developed in 2005.(S.P.E.A.R, 2005).
The first three natural frequencies of the structure are associated with flexion modes of vibration coupled with torsional behaviour due to irregular geometry. The rehabilitated model shows, as seen in Table 1 considerate improvement in frequency domain as well as in overall modal mass distribution in the first three natural frequencies.

Table 4.1. Modal analysis comparative results

Mode	Unretrofitted Str.		Retrofitted Str.	
	Period	Frequency	Period	Frequency
	Sec	Cyc/sec	Sec	Cyc/sec
1	0,673612	1,4845	0,310932	3,3341
2	0,579463	1,7257	0,282893	3,5349
3	0,476984	2,0965	0,225988	4,425

The rehabilitated model displayed a highly improved distribution of modal mass as it can be observed from the 3rd mode of vibration, represented in Figure 4.1. In the unretrofitted model, the torsional centre shifts from one storey to another closer to the edge of the building due to the improper connections of beams and columns and misalignments between structural elements.



(a) (b)

Figure 4.1. Torsional mode shape in unretrofitted structure(a); pure torsion mode shape in retrofitted structure(b)

Occurrence of torsion is due to the plan irregularity resulting from the higher stiffness of the column C6 and the balcony in one of the sides of model. In the modal analysis it can be observed that the torsional centre of each floor has shifted from the outer extremity of the building to the central part thus resulting in higher overall rigidity and lateral resistance.

The three modes of vibration mobilize in x and y direction respectively 90% and 55% of modal mass, while the third mode can be considered a pure torsion mode due to the position of the rotation centre close to the floor mass centre.

4.2. Comparative Dynamic Time History Analysis Results

Within the dynamic time-history(T-H) analysis there were evaluated the comparative maximum structural responses of each storey, in order to evaluate the amplification of structural responses due to the initial faulty design. There were monitored three points for maximum displacements and accelerations, corresponding to each level of the SPEAR structure, as displayed in Figure 4.2.

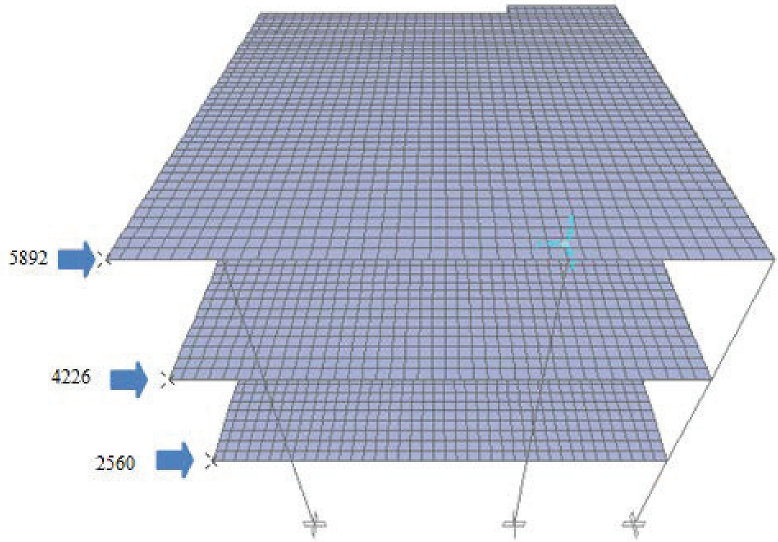


Figure 4.2. Points of interest in the computation of maximum structural response in T-H analysis.

Following the computation of maximum absolute displacements along the two main orthogonal directions X&Y from the T-H analysis we can observe a significant decrease of values on each level of the structure due to the chosen retrofitting solutions. As we can observe in Figure 4.3 and Figure 4.4 the effects of the two types of earthquakes is different on the structure on each direction. While on X direction the deep thrust earthquake from Vrancea area has a significant effect of shear on the base of the structure, the Herceg Novi earthquake amplifies the structural response of the building from the base upwards. On Y direction both earthquake tend to have a similar pattern of base shearing with slight amplification of effects from one level to another.

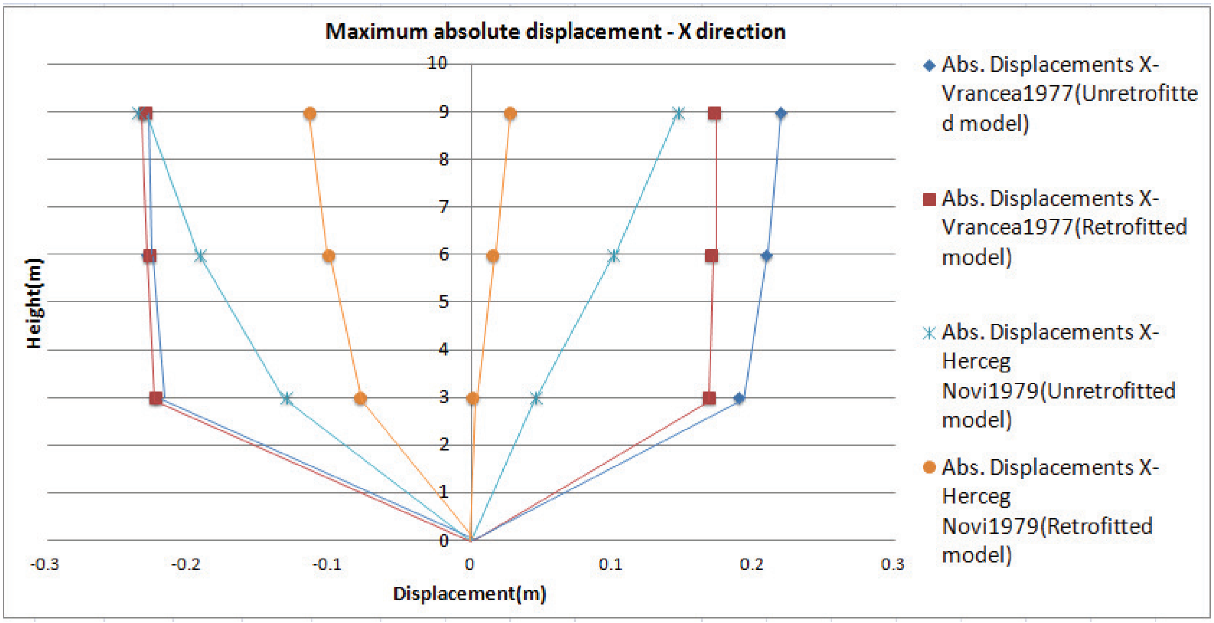


Figure 4.3. Maximum absolute displacements upon X direction in T-H analysis.

The numerical rehabilitation process is also visible on the maximum absolute displacement charts as displayed in Figure 4.3 and Figure 4.4 where we can observe significant decreases in structural response in both directions.

The most significant improvement of the structural response is on X direction where the maximum displacements have decreased from 22 cm to 17 cm considering the Vrancea 1977 earthquake's acceleration and, in the Herceg Novi 1979 earthquake's case, from 15cm they have decreased from 15cm to 3 cm. The same patterns of structural improvement have been observed upon Y direction of the, model, but on a slightly smaller scale.

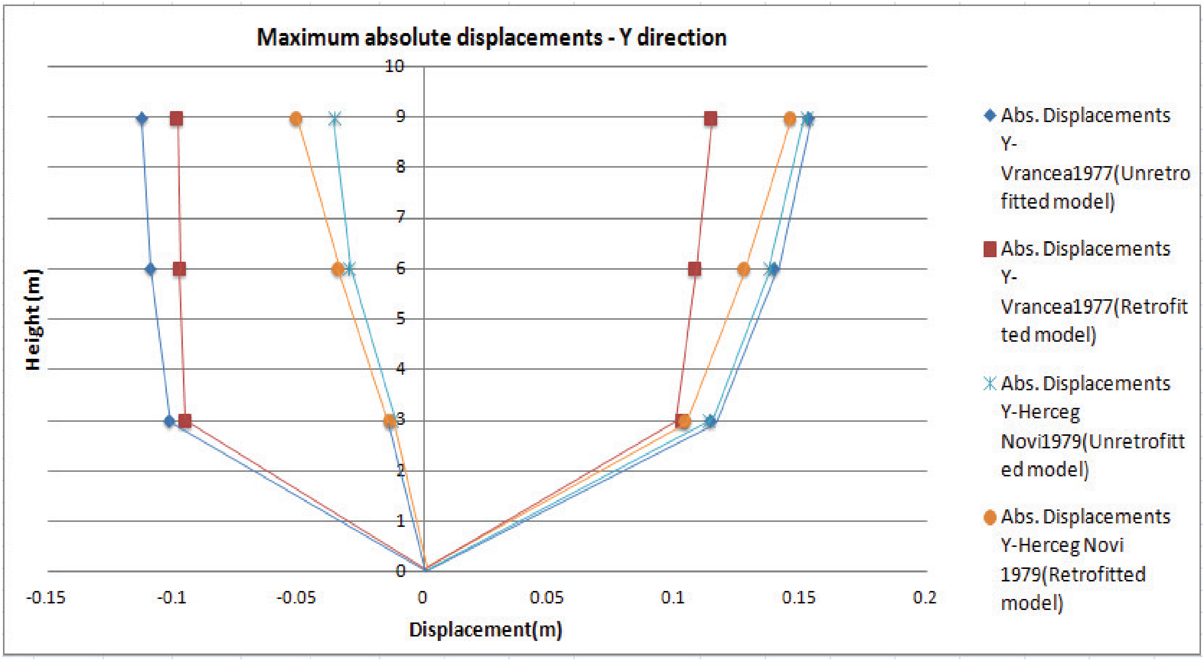


Figure 4.4. Maximum absolute displacements on Y direction in T-H analysis.

5. CONCLUSIONS

The numerical studies done on the SPEAR experimental model have shown that we can enhance significantly the structural behaviour of a building by conducting a thorough research in structural design flaws and addressing them in a proper way. The numerical studies presented in this paper have provided a quick and powerful tool that finds the best structural rehabilitation solution for existing building. It makes for a cost-free and non-time consuming procedure which can make the difference between choosing the right solution for each particular case in the structural rehabilitation industry.

The SPEAR experimental model first underwent a series of numerical trials, in the in-field configuration, unveiling similar numerical results with the ones obtained in the experimental campaigns sustained by other researchers, (Mola, 2005).

Studies like this one can be useful example of precise and rapid estimation of the feasibility of considering multiple rehabilitation solutions, thus helping improve the quality of the built environment and ensuring a better use of the building materials.

6. REFERENCES

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