Estimation of seismic response improvements on RC buildings with innovative "HD" infill walls panels

I. S. Idrizi
Arting5 - Company for engineering design, construction and investments

D. N. Ristic
University Ss. Cyril and Methodius, Earthquake Engineering Institute - IEEES, Macedonia

Z. S. Idrizi
University of Prishtina, Faculty of Civil Engineering, Kosova

SUMMARY
As capacity design philosophy suggests, the best way to achieve a safe seismic response of multistory buildings, under strong earthquakes, is to uniformly spread the inelastic deformation demands throughout the building structure. Unfortunately, this type of mechanism is difficult to be reached due to the abundant presence of infill wall panels on buildings, which under strong earthquakes show severe cracks and strength degradations, thus complicating the seismic response of buildings. In order to avoid these brittle mechanisms of failure, studies were made on increasing the ductility level of infill walls while avoiding any strength degradation. Development of such "HD – high ductility" infill wall panels, would greatly contribute to many important aspects, like the increase of structural strength resistance, drastic reduction of damages under strong earthquake events, achievement of larger structural ductility levels and avoiding any unpredictable local failure mechanisms on buildings.

Keywords: HD infill walls, high ductility infill walls

1. GENERAL INTRODUCTION

Based on many collected data and in-situ observations from past earthquakes, it was concluded that prior to failure of structural members almost all the time significant damage occurs to infill wall panels in buildings (Figure 1). The reason for this phenomenon, as it is already known, is due to the mechanical properties of infill wall panels vastly used today, which are characterised with high brittleness and very low ductility levels. Because of these features, the positive effect of infill walls on the seismic response of buildings can be taken in to account only in the linear stage of structural behaviour since there are no plastic deformations in the building. However, under stronger earthquake events, buildings are subjected to larger deformations followed up with noticeable cracks and strength degradation of infill wall panels. This stage of structural response can be very dangerous for RC buildings, since a sudden failure of infill walls would impose unwanted local failures to RC structural members resulting to a severe degradation of RC member elements followed by a total structural collapse.

Considering that infill wall panels are present almost in every building, with more than 80% of participation percentage on building frames, it is obvious that a modification of the mechanical properties of infill walls, would greatly affect the seismic response of the overall building. In the search for improvement of mechanical characteristics of infill walls, a new system of infill walls has been conceptualized, namely "HD" high ductility infill wall system, which in general is expected to show noticeable increase on ductility without any strength degradation.

The objective of this paper is to present the innovative HD infill wall systems and also to demonstrate how they will improve the seismic response of RC buildings when implemented in buildings. For demonstration purposes have been developed three mathematical models representative for a seven story building where both conventional and innovative HD infill wall systems were considered. These models have been carefully analyzed using advanced analysis procedures. This paper presents the most characteristic results which aim to show the level of seismic response improvement of buildings with HD infill wall panels.

Figure 1. Stages of infill wall failure on RC structures (from small cracks up till total collapse)

2. MATHEMATICAL MODELING

In order to demonstrate the seismic response improvements of buildings with HD infill walls in respect to buildings with classical infill walls, there have been generated three variations of mathematical models representative for the 7 storey building (Figure 2), using SAP2000 v.14 program.

The first model (CONV-A, Fig.3-left), represents a dual structural type of a 7 storey RC building without consideration of infill walls panels. In the second model (CONV-B, Fig. 3-middle)
are included the conventional infill walls consisted of hollow clay brick units, while the implementation of HD infill wall panels in the RC building is represented by the third model (HD-A, Fig. 3-right).

The "CONV-A" and "CONV-B" mathematical models are a 3D representation of the existing building shown in Fig. 1. CONV-B was used during the design and construction phases of this building 3 years ago, while the CONV-A is studies for the single purpose of observing and comparing the effects that both conventional and HD infill wall panels pose to the building with no infill wall panels. Differently to both CONV mathematical models, the "HD-A" model represents the implementation of High-Ductility "HD" devices on conventional infill wall panels, thus upgrading them to so-called "HD" wall infill panels.

All material properties of structural and nonstructural elements and loading characteristics remain identical to all of the three models.

In consideration to the load analysis, it can be outlined the overall gravitational load (self weight, dead load and live load) weighting about 6000t. The material used for all structural members (columns, walls, beams and slabs) is reinforced concrete with concrete class C30/35 and steel class S400.

Proportioning of bearing members, amount of reinforcement and reinforcement detailing along all structural elements has been adopted based on the seismic design criteria of Eurocode 8. Thus, a satisfactory response is achieved for both CONV-A and CONV-B models. All column cross sections at the ground story are with dimensions 50x50cm and the thickness of the core walls is 40cm. A detailed representation of the geometrical properties of structural bearing elements are not in the scope of this study, therefore they are not shown in this paper.

Figure 2. 7 storey constructed building in Shkup, Macedonia, 2009

During phases of modeling generation there have been adopted many parametric assumptions which greatly affect the dynamic nonlinear behavior of all three models. Some of these parameters are the properties of infill wall brick units, nonlinear modeling of RC wall and slabs and plastic hinge modeling of RC frame elements at critical regions.

In order to realistically estimate the nonlinear response of RC frame elements (columns and beams), which is crucially important for the seismic performance of all three models, the fiber hinging approach was used. The length of fiber hinges was adopted to be 30% of the relative length of frame elements it was assigned to, while controlling parameters of hinges are automatically obtained from the cross-sectional geometry of frame elements and their reinforcement detailing. The type of frame hinging was assumed as fiber P-M2-M3 for both column and beam elements. The frame hinges were generated for all column and beam elements located on the basement, ground story, story 1 and story 2, since the nonlinear behavior of the bottom stories of the building is to our greatest concern.

As infill wall panel constituents have been adopted the hollow brick units consisted of clay material. The thickness of infill wall panels, respectively clay brick units, has been adopted 16cm. The compressive strength of brick units was assumed 3,0MPa. Using empirical formulations on describing the nonlinear behavior of infill wall panels, there were determined the stiffness and strength parameters for the particular infill wall panels used on CONV-B model. Using SAP2000 computer program, the nonlinear modeling of these infill wall panels was done based on the diagonal strut modeling concept by the use of nonlinear link elements with multi-linear plastic properties. The nonlinear modeling if these infill wall panels is shown in Figure 4.

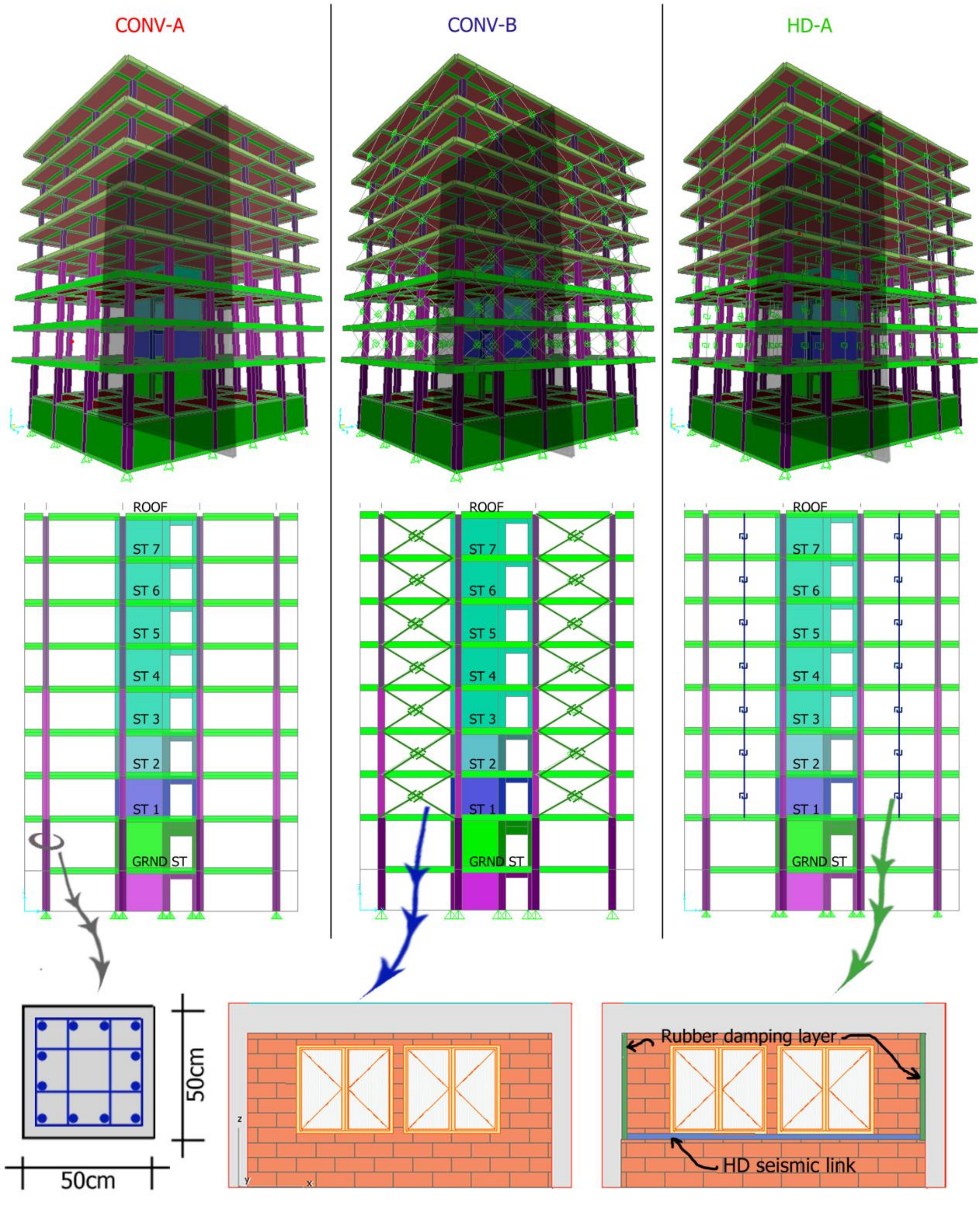

Figure 3. 3D mathematical models representative for the 7 storey building constructed in Shkup, Macedonia

3. MODELING CONCEPT OF "HD" INFILL WALL PANELS

The concept of "HD" infill wall panels emerged as a need to develop a wall paneling system that would show high levels of shear deformations under extreme seismic events, without being subjected to cracks and strength losses, while still contributing to the lateral strength capacity of buildings with their lateral bearing capacity. Considering the brittle nature of infill wall brick units (as constituents of the conventional infill wall panels) the increase in ductility level of conventional infill wall panels was achieved through introduction of special link elements within the panels, having perfectly stiff-plastic hysteretic characteristics (Figure 4). As will be demonstrated in the next section, this solution is very effective toward protecting the structural integrity of infill walls (with or without doors and windows), by controlling the maximum level of shear forces resisted through infill walls.

As shown in Figure 4, below, solid clay brick units are constituents of both conventional and HD infill wall panels. Figure 4-left shows the infill wall panels representative for the CONV-B model. This infill wall panel system is a conventional system and it is already elaborated through many studies both experimentally and analytically. According to Figure 4-left, it is observed how the horizontal force **V** is transferred transfered from the top/left side of the frame to the bottom-right side through the entire infill wall panel element. Moreover, the graph of Figure 4-left shows the envelope curve of the hysteretic behavior. This demonstrate the "high brittelnes/low strength" propertiy of conventional system of infill wall panels.

On the other side, Figure 4-right shows the infill wall panels representative for the HD-A model. This infill wall panel system is a now improved system called High Ductility "HD" infill wall panel system. What is actually making HD panels different from the conventional ones, is the introduction high-ductility "HD" link elements somewhere within the panel and cutting it horizontally from one end to the other. The infill wall panel on the upper side of the seismic link element should not be attached with adjacent column elements though. There must be a minimum gap of 4cm between the infill panels and columns to allow the upper side of the wall to move freely without making any contact with column elements. The gap between the column elements and the infill wall panels above the horizontal "HD" element, may be filled with soft insulation or rubber materials.

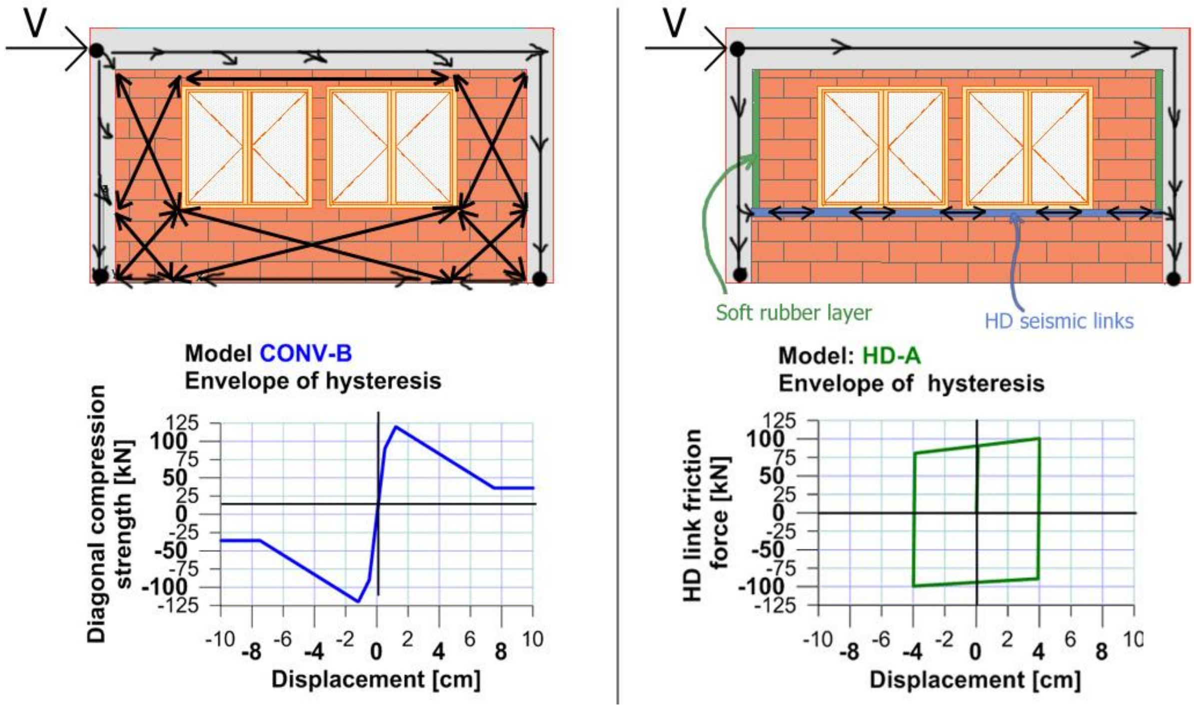

Figure 4. Response mechanism of conventional and HD infill wall panels

After establishing these constructive adjustments, the next step is to design the HD links element properly. The design of HD link elements represent the determination of an optimal stiffness and yielding strength of HD link elements. First, the initial stiffness of HD elements must be considerably stiffer that the actual stiffness level of conventional part of infill panels and, second, the yielding strength of HD elements must be slightly lower than the actual shear strength of the conventional part of infill walls.

Determination of these two properties of HD seismic links is very crucial for the securing the prescribed response mechanisms of HD infill wall panels which is also shown schematically in Figure 4-right. A stiffer HD link makes sure that the shear forces acting on the infill panels are firstly absorbed from HD links and then transferred to other structural elements through the conventional part of infill panels. On the other hand, a weaker HD link than the shear strength of the conventional part of infill wall panels limits the maximum level of shear forced transferred through the conventional part of infill wall panels. This way infill wall panels remain linear while the entire plastic deformations within the infill panels are concentrated on the seismic HD link elements. In Figure 4-right is also demonstrated the transfer of forces through the HD seismic links, thus the conventional parts of infill wall panels remain linear.

4. SEISMIC RESPONSE VERIFICATION OF BUILDINGS WITH “HD” INFILL WALLS

The seismic response verification of all three building models is done using direct integration time-history analysis. Direct-integration time-history analysis is the ultimate FEM based technique which takes in to account the full nonlinearity features of all elements constituting the mathematical models, and it requires significantly more calculation time to obtain results. While not being the most efficient tool in terms of time duration of calculations, it certainly is the most effective tool in analysis and detection of even the most complicated dynamic behaviors of structural models.

Under nonlinear direct-integration time-history analysis, all three models were subjected to the Izmit earthquake accelerations acting on all three orthogonal directions X, Y and Z. In addition, all three models were the considered with all nonlinear features described earlier in section 2 and 3. For consideration of the high ductility HD devices it was used the plastic (Bouc-Wen) hysteretic model available in SAP2000 computer program.

Some of the most representative results obtained from these analysis, are presented in figures 5, 6, 7 and 8. These figures greatly facilitate in getting a clearer perception on the dynamic response of all three models.

In order to get a basic understanding about the behavior of structures under free vibrations, in this paper are presented the first three vibration modes and vibration periods for all three models, generated from modal analysis. In Fig. 5 are given the first 3 modal periods of vibration for all three study case models CONV-A, CONV-B and HD-B. From this figure can be observed the stiffening effect increasing from CONV-A to HD-A models. This effect, obviously, reflects the consideration of infill walls in CONV-B and HD-A models.

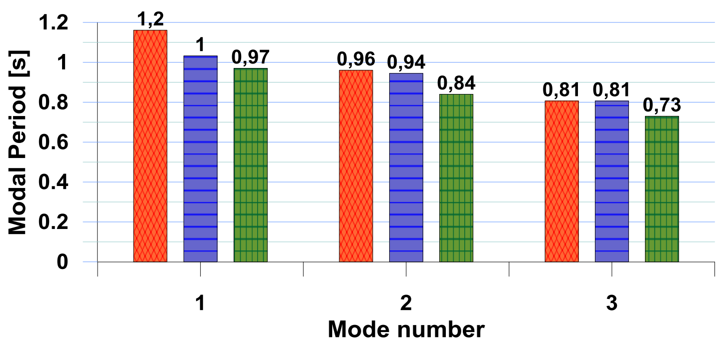

Figure 5. Modal analysis results for all three models

In figure 6, below, are shown the time-history responses of storey displacements of all three models, in X direction. In general, all models show similar responses with gradual reduction of story displacement levels. Thus top lateral displacements about the X direction are reduced from 17.5cm for CONV-A model down to 14 cm for HD-A model. In addition, the envelope curves of lateral displacements along stories of all three models (Figure 7), show the reduction effect of lateral displacements on the Y direction as well.

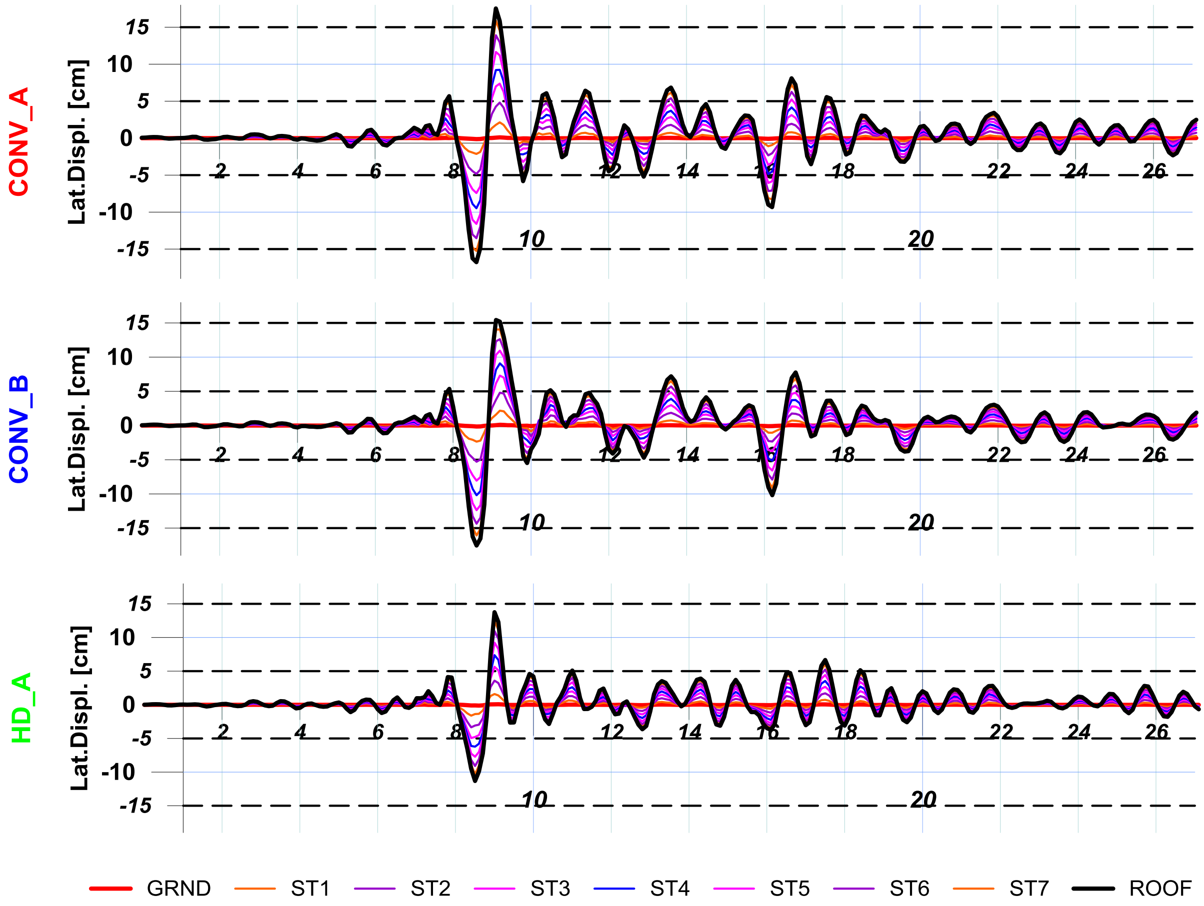

Figure 6. Story displacement time-history of all three models under Izmit earthquake, X direction

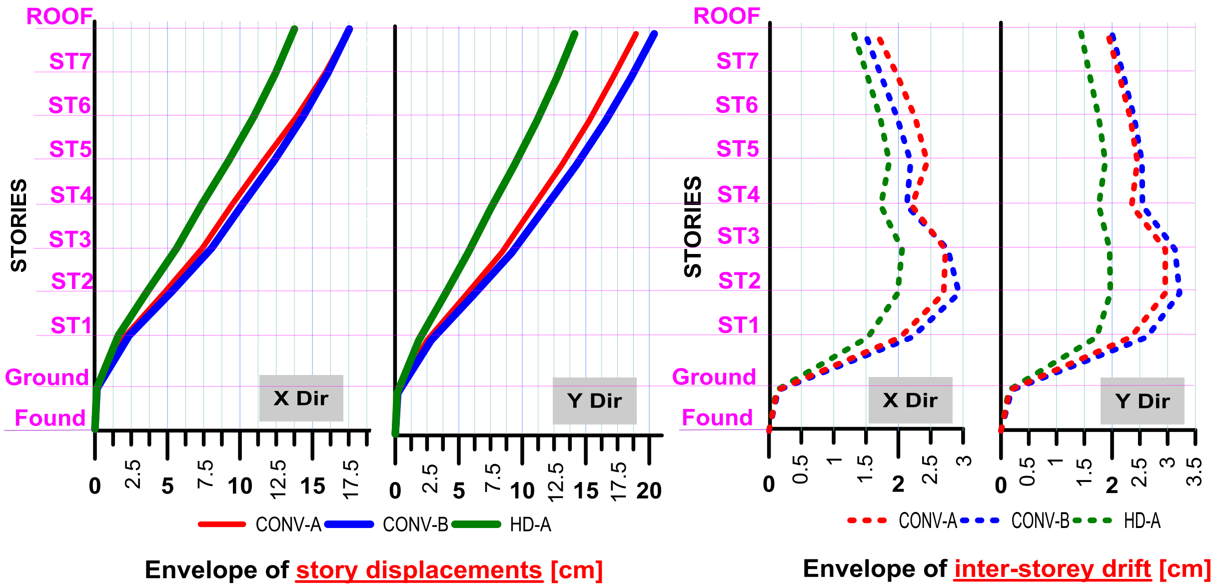

Figure 7. Envelopes of story displacements and drifts in X and Y dir, under Izmit earthquake

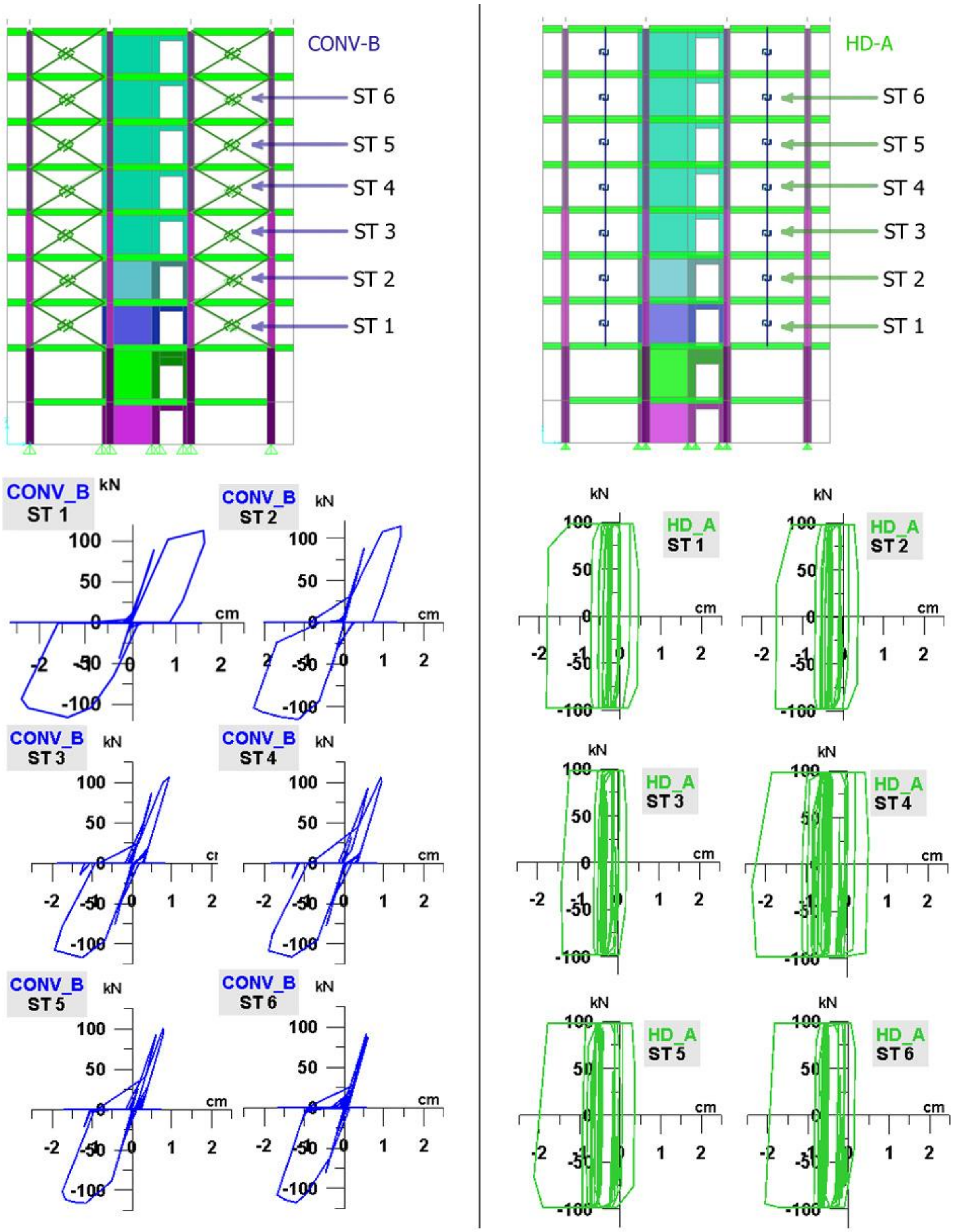

Figure 8. Hysteretic behavior of infill panel element, under Izmit earthquake - X direction

Comparing the displacement responses of all three models (CONV, HYDE-A and HYDE-B) in figure 7, the first thing to be observed is that all three models demonstrate similar response pattern, following the logic of capacity design philosophy, i.e. all stories are proportionally activated for energy dissipation of seismic forces, especially the first three stories (ST1 to ST3). Moreover, due to the lack of infill walls on the ground floor, and because of the higher story height, the story displacements and inter-story drifts of the ground story are somewhat more amplified. The phenomenon of response amplifications usually on the ground stories of multi-storey buildings is widely known as a "soft-story" phenomena. However, nevertheless the soft-story effect, all three models prove to have sufficient strength capacities to successfully resist these amplification effects on the ground story. According to figure 6, all three models respond appropriately throughout the time duration of Izmit earthquake without any permanent displacements, i.e. no offset from the balance line is observed in the time/history graphs.

In Figure 7, presented are the envelope curves of lateral displacements (left) and storey-drifts (right) along the height of all three models. Lateral storey displacement envelopes (figure 6-left) show once again the slight decrease of lateral displacements on the ground story of KD-A model in respect to both CONV-A and CONV-B models. Moreover, the envelopes of lateral storey drifts (figure 6-right) better demonstrate that all the stories respond proportionally to the seismic forces acting on the building. One more thing that should be observed is that the stable dynamic response of all three models is greatly controlled by the RC core wall present at the core of all three models. Actually, due to this RC core wall, which is much more stiffer and stronger in respect to infill walls, the models are not noticeably affected by the upgrading of conventional infill walls with HD infill wall panel system. Although, the improvement effects in terms of lateral building strength is expected to be much higher on "frame" types of structures.

The differences between the conventional and HD infill wall panels are obvious and quite interesting. According to figure 8, conventional infill wall panels (figure 8-left) show excessive nonlinear behavior at the bottom stories while rising to the upper stories they get reduced down to almost no nonlinearity at all. Moreover, the conventional infill wall panels show non-symmetrical hysteretic behavior throughout all stories of the building.

Contrary to the conventional infill walls, the HD infill wall panels (Figure 8-right), demonstrate a quite stable dynamic response throughout the entire height of the HD-A model. There is not evident any strength degradation. The hysteretic response, although stable, it is shifted to the left of the balance line which after earthquake event automatically returns back to the initial position along with all other structural elements of the building.

5. CONCLUSIONS

Considering the brittle nature of infill wall panels and the relatively low lateral strength capacities, they are generally applied for fulfilling the architectural requirements and not to serve as load bearing or lateral resisting systems. By this paper, it has been endeavored to present an innovative idea of making minor adjustment on conventional infill walls in order to improve the structural response of conventionally designed buildings. According to this study, by introducing HD infill walls on conventional buildings, no cracks or strength degradation of infill walls occurs anywhere. Consequently, any unpredictable local failure mechanisms on structural elements due to concentrated stress releases for infill walls failures are completely avoided. In addition, depending on the structural type of buildings, there are expected slight to moderate improvements on structural strength and structural ductility level.

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