SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

MODELLING OF AN ENERGY DISSIPATOR FOR PRECAST RC CLADDING SYSTEMS

Eleni SMYROU[1], Ahmet GÜLLÜ[2], Ercan YÜKSEL[3], Hasan ÖZKAYNAK[4], and Faruk KARADOĞAN[5]

ABSTRACT

Claddings in prefabricated RC structures are used for architectural reasons and, being classified as non-structural elements, they are not designed to contribute to the lateral load capacity of the structure. Recent earthquakes, such as Kocaeli, 1999 and L'Aquila, 2009, proved that the seismic design methodology followed for the design of claddings is not sufficient.

A series of component tests on a dissipative connector, intended to be installed between cladding panels, have been carried out in the Structural and Earthquake Engineering Laboratory of Istanbul Technical University as part of the on-going FP7 project named Safecladding. The connectors are made of ordinary steel, a material practitioners feel confident with, in a shape that can be easily and at low cost produced in workshops on site. The purpose of this paper is to investigate available options for a suitable model for accurately modelling the cyclic response of the energy dissipator tested. Two different modelling strategies have been followed: i) use of shell elements, and ii) use of beam elements. Geometrical and material nonlinearities have been included in the models. Material properties have been taken from the tests. The examined specimens have been subjected to shear cycles with zero axial load.

INTRODUCTION

Claddings in prefabricated RC structures are used for architectural reasons; their contribution to the overall load bearing system has not been subject of detailed research. The design of the claddings has traditionally been based on the assumption that they neither interact with the system nor induce adverse effects with respect to the structure's seismic response. In other words, the design of the prefabricated structure and of the claddings is conducted completely individually with zero interaction assumed between the two.

Taking advantage of the lateral stiffness of claddings could possibly be considered if one needs to decrease the displacement and force demand on the RC precast columns of the main structure. Connecting the claddings to each other and/or to the load bearing system could be an option too; however the degree of this connection is disputable and certainly would need to be established with precision if it was to be included in the design. A useful alternative, investigated in this work in detail, is employing energy dissipating connectors for cladding-to-cladding or cladding-to-structure connections so that a certain level of energy is dissipated within the connectors through hysteresis. The

[1] Asst. Prof. , Dept. of Civil Eng, Istanbul Tech. Univ., Istanbul, esmyrou@itu.edu.tr
[2] PhD candidate, Dept. of Civil Eng, Istanbul Tech. Univ., Istanbul, ahmgullu@gmail.com
[3] Assoc. Prof., Dept. of Civil Eng, Istanbul Tech. Univ., Istanbul, yukselerc@itu.edu.tr
[4] Asst. Prof., Dept. of Civil Eng., Beykent Univ., Istanbul, hasanozkaynak@beykent.edu.tr
[5] Emer. Prof., Dept. of Civil Eng, Istanbul Tech. Univ., Istanbul, karadogan@itu.edu.tr

type of connector that is investigated in this paper is a steel device that can be placed between the claddings, at the bottom of the panels or beam-to-cladding connections. Similar devices in shape, material and concept, have been proposed by Kelly et al. (1972) and recently reintroduced by Baird et al. (2014) as an efficient means of energy dissipation to be applied in coupled walls. Note that the devices in the work by Kelly et al. (1972) and Baird et al. (2014) are U-shaped, practically of half section compared to the ones presented in this work that have closed section (Figure 1).

A series of component tests on a dissipative connector have been carried out in the Structural and Earthquake Engineering Laboratory of Istanbul Technical University as part of the on-going FP7 project named Safecladding. The connectors are made of ordinary steel, a material practitioners feel confident with, and in a shape that can be easily and at low cost produced in workshops on site. Information on the testing campaign, the experimental test-up and details of the connectors can be found in Ozkaynak et al. (2014).

The purpose of this paper is to investigate available options for a suitable model for accurately modelling the cyclic response of the energy dissipator tested, as shown in Figure 1. Two different modelling strategies have been followed: i) use of beam elements, and ii) use of shell elements. Geometrical and material nonlinearities have been included in the models. Material properties have been taken from the tests. The examined specimens have been subjected to shear cycles initially with zero axial load, while tests of pure axial load (tension –compression), as well as of combined shear and axial load are scheduled to take place too.

Figure 1. The testing setup (left) and the deformed specimen under shear loading (right)

Cushions were subjected to a cyclic shear loading protocol that has been generated according to FEMA 461 (2007).

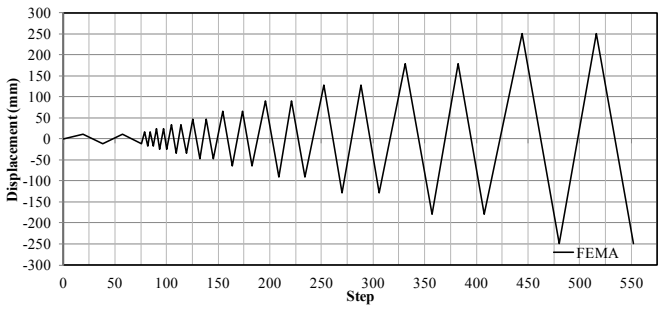

Figure 2. Load pattern applied to the specimens

The connectors in question have produced a stable ductile loop during the tests. This is because the connector can take advantage of steel properties, which provide high stiffness in the elastic range as well as energy absorption with moderate strain hardening when deformed beyond elastic limit. The main mechanism mobilised by the proposed dissipator is flexure. In this stage essential information regarding the stiffness, strength, as well as the characteristics of individual cycles, have been extracted. In a second stage this information is expected to be used in order to derive further conclusions related to the hysteretic energy and damping properties, as well as the displacement limits

of the connectors. The main goal of the analyses presented in this paper is to accurately reproduce the tests results so that more connector types under various loading combinations can be analysed afterwards with a level of confidence on the numerical models used. It is also aimed that a suitable modelling strategy is established so that the connectors can be placed in larger numerical models representing the entire structure, as dissipating components.

FRAME MODELLING APPROACH

The first approach followed for modelling the structural response of the cushion is by means of frame elements. SeismoStruct software (SeismoSoft, 2014) is employed for the analyses. Geometric nonlinearities are taken into account. The cushion is divided into 48 pieces. Each piece represents a ~13cm long, 10cm wide and 3, 5 or 8mm thick steel frame element as cushions of different thicknesses were examined (Figure 3). The curved parts have been discretised every 15° degrees. The number of elements used, though not excessive, is sufficient for smooth representation of geometry and acquirement of results without any numerical instability. The frame elements are modelled by using distributed plasticity members with force-based formulation. Three Gauss-Lobatto integration points are used per member.

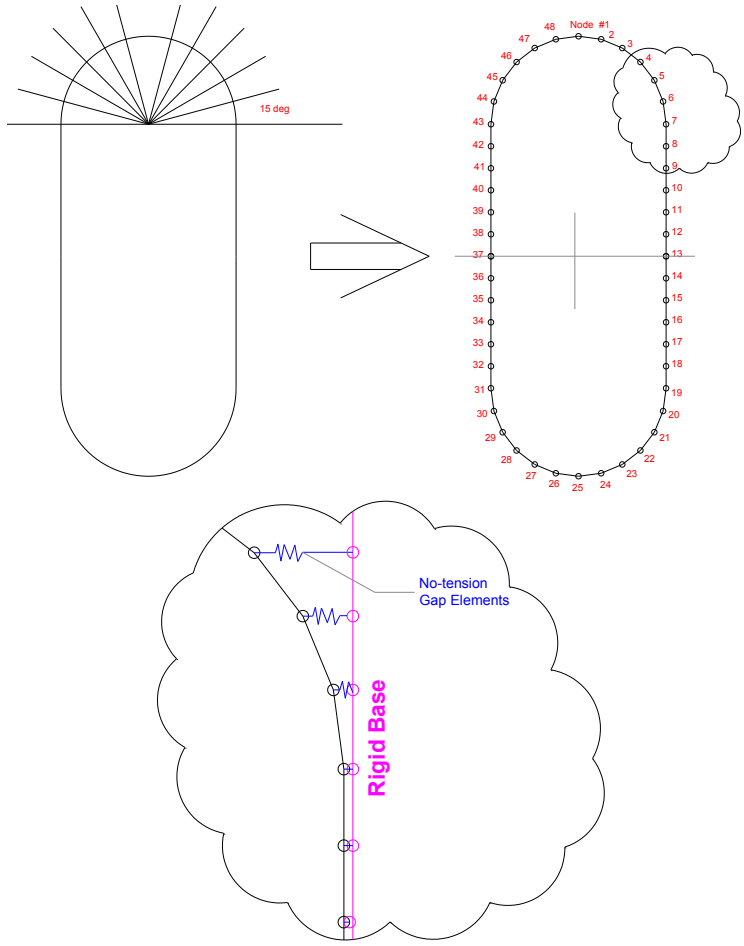

Figure 3. Discretization of the cushion elements (above) and the representation of the contact problem (below)

The main challenge in the model was the accurate representation of the contact problem. No-tension zero-length gap elements are used for representing the contact between the frame elements and an imaginary surface (Figure 3 and Figure 4). According to the notation of the backbone curve given in Figure 4, the positive gap displacement is inserted as a very large value, ensuring that under any condition the gap element is not activated in positive (tension) direction. The positive stiffness is given as a very small number, so that in the positive direction, when the relevant structural node departs

from the surface, no resistance occurs. The gap in the negative direction, on the other hand, is the initial physical horizontal gap between the original position of the relevant node and the rigid surface. The displacement value for each gap element varies according to the geometric position of each node. The stiffness in the negative direction is a very high value (infinite) so that the contact of the cushion to that stiff immovable base (cladding in reality or steel pad surface in the test) is represented correctly.

The cyclic response of the steel material is represented using the Menegetto-Pinto (1973) model that is implemented in SeismoStruct. Strength and hardening parameters of the model are defined by using the material coupon tests conducted per TS138 (2004). Since the material response primarily depends on these two fundamental parameters, i.e. strength and hardening, an approach that balances the effects of these two parameters on the overall response had to be followed. The strength parameter controls the response in the post-elastic phase before the very high nonlinearity is initiated. The hardening parameter, on the other hand, plays a definitive role in the very high plasticity phase. The approximate bilinearization done over the curve obtained after material tests and finally assumed in the material model in SeismoStruct is presented in Figure 6 to Figure 8.

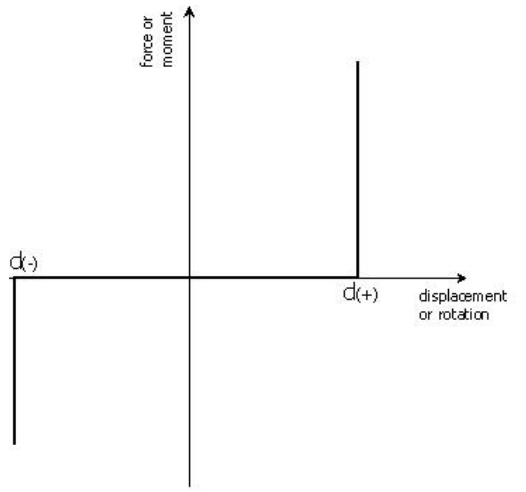

Figure 4. General behaviour of the gap element

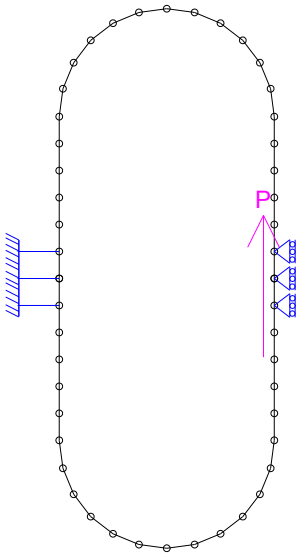

Figure 5. Boundary conditions used in the frame model

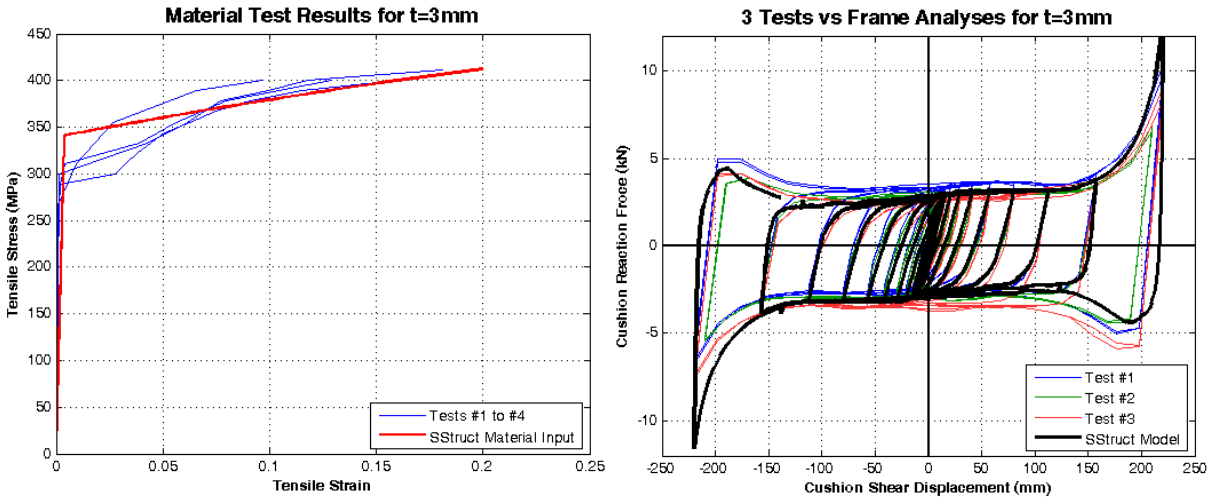

Figure 6. Material test results and the assumed material model and the comparison of the pure shear tests on the cushions with the results of the frame model for t=3mm cushion

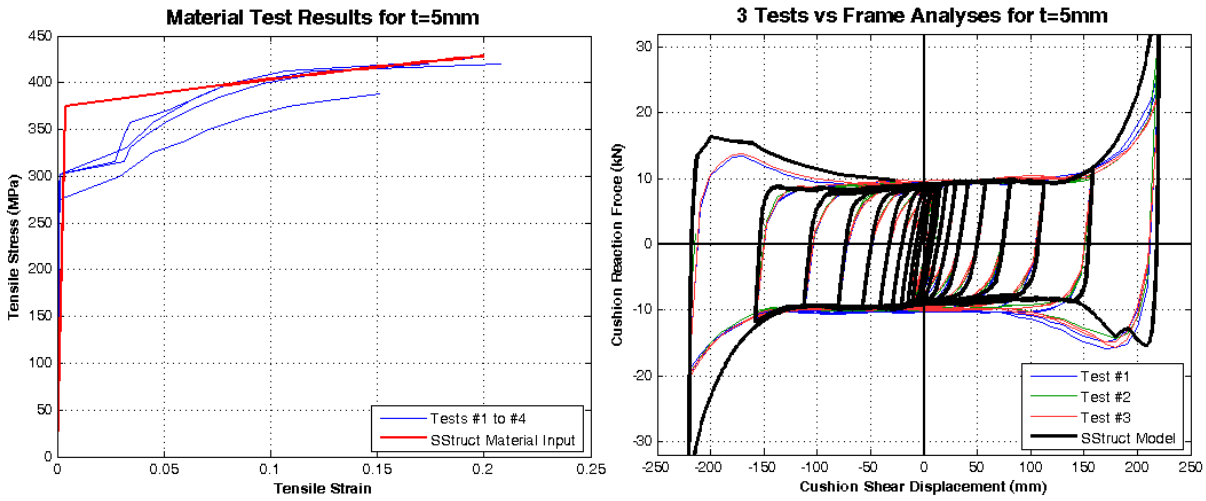

Figure 7. Material test results and the assumed material model and the comparison of the pure shear tests on the cushions with the results of the frame model for t=5mm cushion

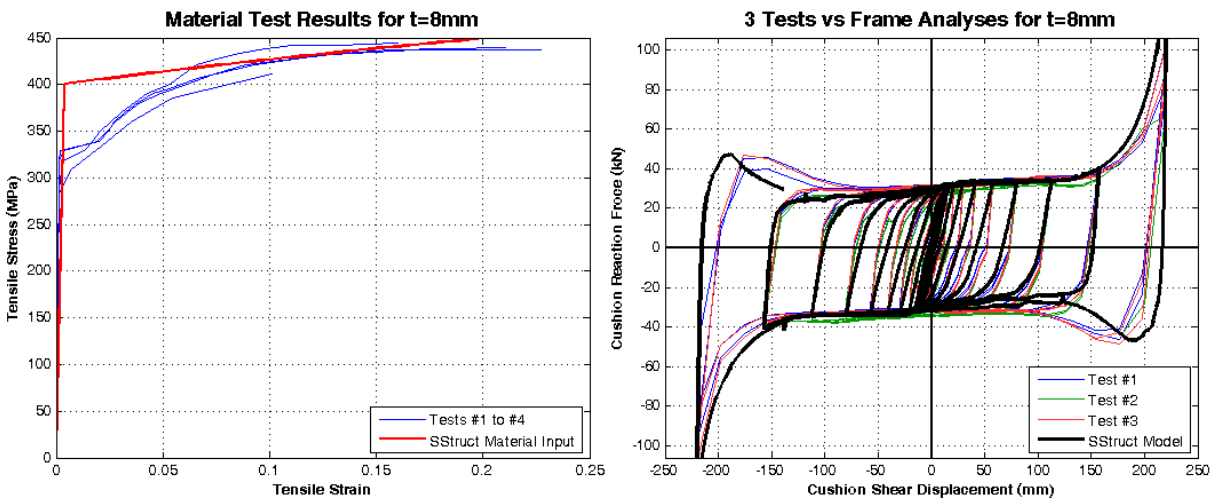

Figure 8 Material test results and the assumed material model and the comparison of the pure shear tests on the cushions with the results of the frame model for t=8mm cushion

The boundary conditions of the model are described in Figure 4. According to this, the left side of the specimen is fixed along a 35mm long piece that stands for the physical dimension of the fixing bolt. The load is applied onto the right side, again along a 35mm piece to represent the bolt diameter. The nodes where the load is applied are restrained with roller supports, the rest of the nodes are combined with suitable gap elements.

The results of the analyses conducted on the frame models for the pure shear tests are given in Figure 6 to Figure 8. The material models assumed and the tests results on coupon samples are also provided in the same figures. It can be readily seen in the aforementioned figures that the frame model can predict the stiffness and strength of the cushions accurately enough. Besides that, the unloading and reloading curves, parameters of prime importance for calculating the hysteretic energy dissipated by the cushions, are also satisfactorily captured. In overall, model consisting of frame elements attains to represent the response of the cushion under cyclic shear loading.

One phenomenon that can be observed in the cyclic hysteresis curves in Figure 6 to Figure 8 is that the strength and stiffness increase drastically in the very last cycles. This phenomenon occurs when the differential displacement between the two bolts (i.e. two anchoring points of the cushion) reaches to a level where the geometry of the cushion does not allow further the "rolling" effect to be developed. In that phase the cushion is subjected to pure tension, acting as a tie between the two bolts. This part of the hysteresis curve is affected by several parameters, such as the welding conditions, direction of the bolt nut etc. The behaviour becomes quite complex after the cushion is tensed between the two nuts (see Figure 9), but for this very reason this part of the behaviour will not be used in design as deemed to be not reliable.

Figure 9. The deformed shape of the cushion at the very last cycle (left), and a failure mode at the last cycle (right)

FINITE ELEMENT APPROACH

In parallel, a finite element model has also been created by using ABAQUS ver. 6.10 which offers multiple material modelling capabilities and advanced computational options.

Using 2D finite elements the cushion has been simulated between two rigid surfaces defined as boundaries. In the inner side of the cushion, plates of 2 cm length have been created with finer mesh accounting for the effects by the bolts used to fix the cushion on the boundary surfaces. The numerical model and the deformed shape of the cushion while "rolling" under imposed loading can be seen in Figure 10. The numerical model has been generated using S4R shell elements (Figure 10).

Material and geometrical nonlinearities are considered during the FEM analysis by using NLGEOM option of ABAQUS. The material plasticity is defined based on the coupon tests for each thickness.

The data on the 'plastic' option corresponds to the true stress and true plastic strain. Therefore nominal results obtained from the coupon tests were converted into the equivalent true stress and true plastic strain values.

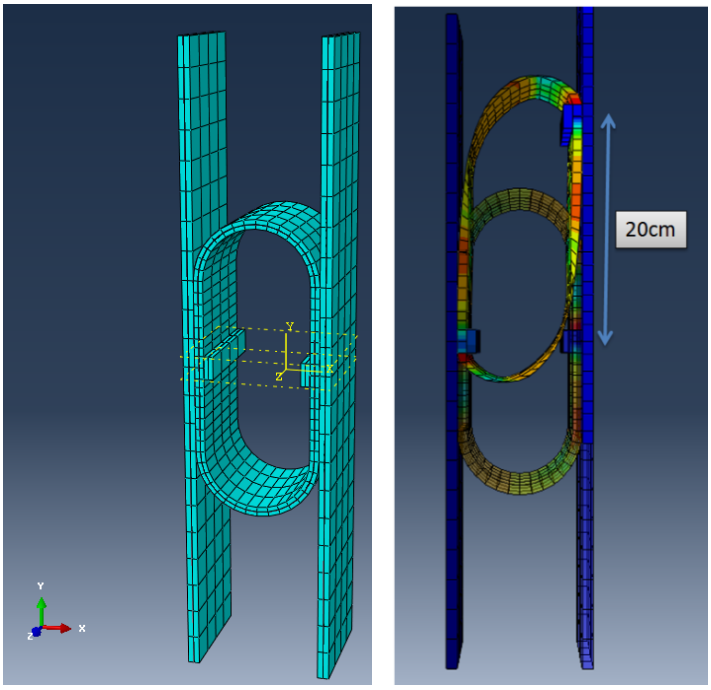

Figure 10. The 3D meshed model (left) and the deformed shape (right)

Another important parameter for defining plastic properties of material is selecting the type of associated hardening. Metals subjected to cyclic loading have to have kinematic hardening model to simulate inelastic behaviour of material (ABAQUS Analysis User's Manual, 20.2.2). The effect of selected hardening option is shown in Figure 11. Clearly the results obtained with isotropic hardening fail to reproduce the experimental response in general and with most characteristic problem the overshooting of strength for a wide range of values. Kinematic hardening is rendered the appropriate modelling choice.

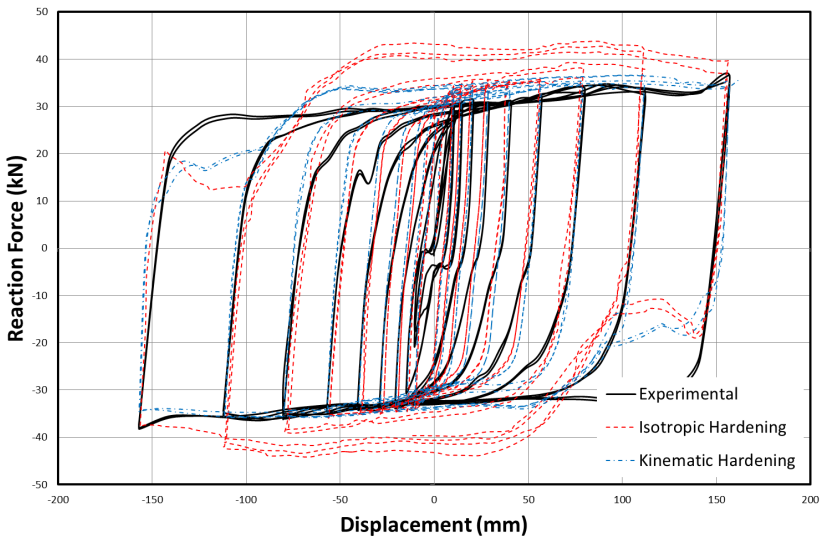

Figure 11. Effect of different hardening options used

The analytical results obtained for different thicknesses are collated with the experimental ones, as shown in the following figures. Though the loading and unloading stiffness are relatively satisfactorily predicted, the numerical model does not exhibit satisfactory match in the estimation of strength. The difference between the experimental and the numerical value of strength is particularly pronounced for the case of 3mm thickness, while for the other two thicknesses deviation from the experimental value is also noticeable. Discrepancy between the experimental and numerical hysteretic

loops appears also in the unloading branches, especially in the larger cycles. Such a discrepancy indicates that the model does not capture the response after plastification and large deformations associated with changes in geometry have occurred, and thus improvements are required.

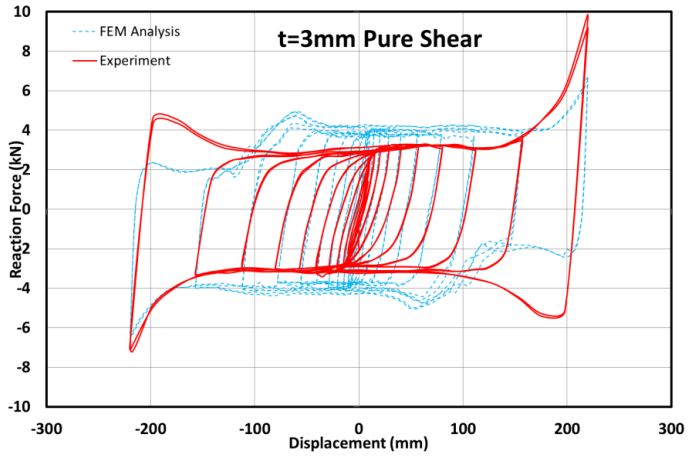

Figure 12. Comparison of the experimental and the analytical results of the FE model for t=3mm thickness cushion

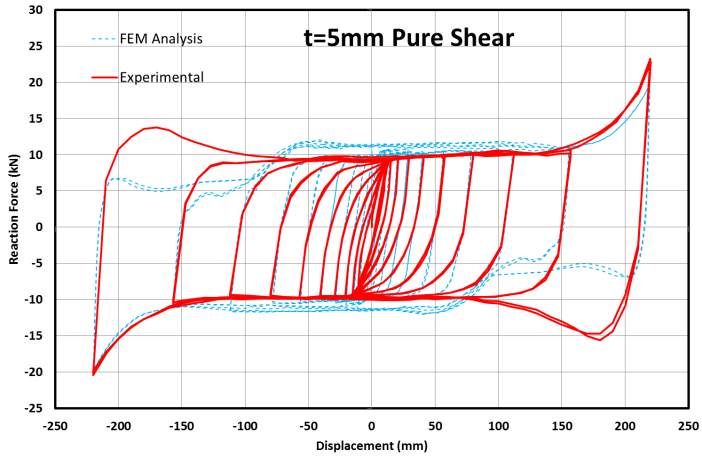

Figure 13. Comparison of the experimental and the analytical results of the FE model for t=5mm thickness cushion

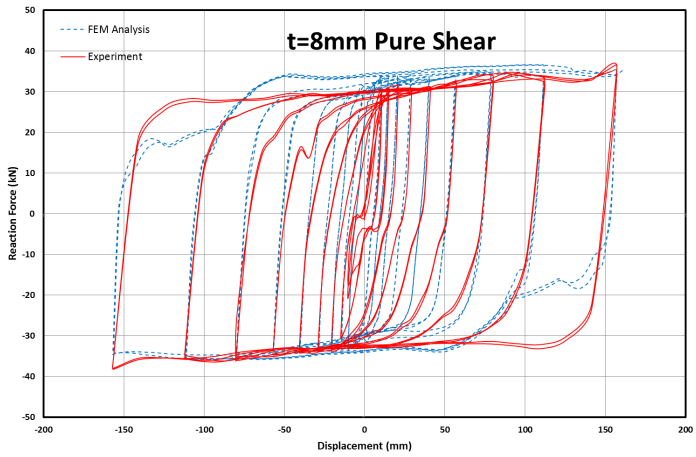

Figure 14. Comparison of the experimental and the analytical results of the FE model for t=8mm thickness cushion

CONCLUSIONS

A series of tests on a new dissipative device, intended to be used in the connections of claddings to cladding or the main structure, have been executed within the framework of on-going FP7 project named Safecladding. The connectors, made of steel and in shape of a cushion, have been subjected to cyclic shear loading. Their hysteretic response, obtained experimentally, has been simulated numerically following two different modelling approaches. In the first, beam elements have been employed in conjunction with gap elements in order to represent the contact issue. The comparison between the experimental and numerical results obtained with this approach exhibit a satisfactory match. Properties critical for the description of the response of the cushion, such as the strength, the loading and unloading stiffness, are well predicted allowing the conclusion that this modelling approach can provide reliable results regarding the response of the cushions tested, as well as of other devices of similar properties, with a relatively limited modelling effort and computational cost. The second modelling option included the use of shell elements, a robust but heavier computationally option. The results obtained managed to describe the overall response of the cushions, however, discrepancies in the prediction of strength have been noticed. This fact, in combination with some issues related to the response after plastification, highlights the need for improvements in the model with shell elements. Care should be taken so that such refinements of the model do not render the analysis more cumbersome.

REFERENCES

ABAQUS (2011) Research Edition, FEA: Providence, RI, USA.

Baird A, Smith T, Palermo A, Pampanin S (2014) "Experimental and Numerical Study of U-shape Flexural Plate (UFP) Dissipators", *Proceedings of the 2014 New Zealand Society of Earthquake Engineering Conference,* Auckland, N.Zealand, 21-23 March.

FEMA 46 (2007) Interim Testing Protocols for Determining the Seismic Performance Characteristics of Structural and Nonstructural Components, Applied Technology Council, Redwood City, California.

Kelly JM, Skinner RI, Heine AJ (1972) "Mechanisms of Energy Absorption in Special Devices for use in Earthquake Resistant Structures", *Bulletin of the New Zealand Society for Earthquake Engineering*, 5(3).

Menegotto M, and Pinto PE (1973) "Method of Analysis for Cyclically Loaded R.C. Plane Frames Including Changes in Geometry and Non-elastic Behaviour of Elements under Combined Normal Force and Bending", *Symposium on the Resistance and Ultimate Deformability of Structures Acted on by Well Defined Repeated Loads*, Int. Association for Bridge and Structural Engineering, Switzerland, 15-22.

Özkaynak H, Güllü A, Gökçe T, Khajehdei A, Mahdavi M, Azizisale F, Bal IE, Smyrou E, Yüksel E, Karadogan F (2014) "Energy dissipater steel cushions", *Proceedings of the 2nd European Conference on Earthquake Engineering and Seismology*, Istanbul, Turkey.

SeismoSoft (2014), SeismoStruct – A Computer Program for Static and Dynamic Nonlinear Analysis of Framed Structures.

TS138 (2004) Turkish Standard EN 10002-1, Metallic materials – Tensile testing-Part 1: Method of test at ambient temperature, Turkish Standards Institute, Ankara.