INNOVATIVE SYSTEM FOR EARTHQUAKE RESISTANT MASONRY INFILL WALLS

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ABSTRACT

Severe damages of masonry infill walls in reinforced concrete and steel frames have been observed after many earthquakes. Typically, masonry infill walls are loaded not just in-plane and out-of-plane but also simultaneously in both directions. While the damage due to the in-plane loading is caused by the increase of interstory drift, out-of-plane collapse is induced by high inertia forces perpendicular to the wall. In reality, both effects strongly interact with each other leading to a further reduction of deformation and strength capacity of the masonry infill. Within the project INSYSME the authors proposed the new system INODIS which decouples the frame and the masonry infill by means of specially shaped rubbers placed in between frame and infill. The decoupling reduces the damages and the infill behaves like a real non-structural element. At the same time the special shape of rubber connection prevent an out-of-plane failure of the infill wall. A series of full scale tests on RC frames with clay brick masonry infills have been carried out in order to validate the efficiency of the system. The experimental tests were carried out separately for in-plane and out-of-plane loading as well as simultaneously applied loads in both directions using a special experimental set-up with airbags. Furthermore small specimen tests were carried out to check material characteristics of the components and the resistances of the connections. The experimental results are used as a basis for the validation of the numerical models, developed on micro and macro level. These models can be used for parametric studies to derive simple design rules for everyday practice.

Keywords: Earthquakes; RC frames; Masonry infill walls; INODIS; In-plane and out-of-plane failure; Decoupling

1. INTRODUCTION

In modern constructions, masonry infill walls are used extensively to fill concrete and steel frames. They represent the most traditional enclosure system since they already have demonstrated excellent performance with respect to healthy indoor environment, temperature, noise, moisture, fire resistance and durability. Furthermore infill walls in framed structures are mostly used to separate the internal space of buildings and external environment, because they are easy to build, to rearrange and therefore attractive for the demands of the modern architecture. Hence the use of masonry infill walls in reinforced concrete frame structures is common in many countries. Generally infill walls within frame buildings have been considered as non-structural elements and thus have been neglected in the design process. However, the observations made after medium and strong earthquakes have shown that the presence of infill walls can modify the seismic behaviour of the structure significantly. Masonry infill walls change the dynamic characteristics of the structure, which in return determine the seismic response. Although the relevant standards contain some requirements for infill walls and non-load-bearing partitions, surprisingly they do not describe how these requirements are to be met concretely. In practice this leads to the fact that the enclosure elements are neither dimensioned nor installed correctly. The evidence of this fact is confirmed by recent earthquakes, which have led to enormous damages due to the insufficient design of non-structural walls. The consequences were total collapses.
of buildings and loss of human lives. Based on field observations after earthquakes during recent years, such as in Duzce (Turkey, 1999), L’Aquila (Italy, 2009), Lorca (Spain, 2011), Christchurch (New Zealand, 2011), Emilia-Romagna (Italy, 2012), examples of unsatisfactory masonry infill response have been reported frequently (Figure 1).

![Figure 1. Strong damage of masonry infill walls after L’Aquila 2009 earthquake (Dazio et al. 2009).](image)

In most of the construction solutions masonry infill walls are built in full contact to the surrounding reinforced concrete frame, by filling the top and sides gap with mortar. This construction type is denoted in the following as “traditional” infills. Due to the unfavourable combination of the flexible frame system and the much stiffer masonry infill with quasi-brittle behaviour, traditional infill walls can experience heavy damages under earthquake loading. At the same time their contribution can lead to a completely different horizontal load transfer and unfavourable torsional effects on the building level. Figure 1 shows typical damages of masonry infills due to seismic loading. As it can be seen, heavy damages are present within the wall, but at the same time the wall is at danger to fail in out-of-plane direction. Therefore, it can be concluded that interactions of in- and out-of-plane effects are really important for the seismic resistance of masonry infill walls. These effects are especially pronounced in case of pre-damages in in-plane direction. A substantial reduction of masonry infill resistances subjected to sequentially in- and out-of-plane loading is subject of ongoing research activities and so far reported in just a few publications such as Angel et al. (1994), Shapiro et al. (1994), da Porto et al. (2013), Morandi et al. (2014), Furtado et al. (2016). All these studies showed significant reduction of out-of-plane resistance due to the previous in-plane loading, by reducing the out-of-plane strength up to 50% and in some cases up to about 80% (Calvi and Bolognini 2001, 2004). Pereira et al. (2012) studied the out-of-plane strength reduction due to previous in-plane damage of traditional infill walls. The experimental campaign showed that the firstly applied in-plane cyclic loading caused strong damage within the infill. Especially the highly stressed contact areas between frame and infill experienced heavy damages. The damages along the interfaces caused a substantial reduction of the required support for out-of-plane loading and led to a fast progressive failure of the specimens characterized by a complete movement of the infill wall out of the frame. The reduction is expected since during in-plane displacements of the frame the damage of the connections appear due to relative movements between frame and infill. Riddington (1984) also studied the problems of the connection between frame and infill and concluded that its damage can lead to unfavourable effects.

A second important aspect in case of simultaneous loading is the formation of the diagonal compression strut within the rigidly attached masonry infill accompanied with the detachment of the infill wall from the surrounding frame in the opposite direction. This goes in a line with findings of many authors (Stafford Smith and Carter 1969; Saneinejad and Hobbs 1995) who worked on calculation approaches for the contact length between frame and infill. All studies and approaches showed that the detached parts of the masonry infill without contact to the frame are quite vulnerable to out-of-plane loading. Although damages and collapses of infill walls caused by alternating and simultaneous in- and out-of-plane loading have been observed in past and recent earthquakes, clear design rules in the codes are still missing.
2. EXISTING SOLUTIONS AND EVERYDAY PRACTISE

As it is described so far, a huge effort has been made in order to investigate the behaviour and influence of infill walls on reinforced concrete frames. In that sense, also different solutions for improvement of the behaviour of infills have been developed and proposed. However, improving the seismic behaviour is just one aspect of the development of feasible solutions, because at the same time serviceability aspects, heat and sound insulation as well as fire protection issues must be taken into account. With respect to the static system of the infills, the boundary condition defined by the connection of the infill to the surrounding frame is the key factor for a sufficient in- and out-of-plane resistance. Solutions to enhance the seismic resistance which have been developed so far can be differentiated into three classes depending on the degree of confinement of the masonry wall within the frame. One possibility is to reinforce the infill walls by additional measures in the wall and to connect them to the main structural system (Dawe and Seah 1989; Calvi and Bolognini 2001; da Porto et al. 2013). In this case, the non-structural enclosure element becomes part of the load-bearing structural system and takes over a part of the seismic actions. As a consequence it is no longer possible to change the arrangement of these elements in case of conversions without a new static calculation. Moreover, in practice, the acceptance of this kind of solutions is low, since the strengthening measures are generally complex and the question quickly arises whether the use of reinforced concrete is more effective with the same economic feasibility. Alternatively, it is possible to provide deformation possibilities within the wall, so that the deformations imposed by the main structural system can be absorbed without damages. For this purpose, special measures like additional sliding surfaces within the wall are needed (Mohammadi and Akrami 2010 and 2011; Preti et al. 2012; Verlato et al. 2016; Morandi et al. 2016). Such system approaches are effective, but not easy to apply in everyday practice because they require a precise installation. The third possibility presents a decoupling of the main structural system and the infill walls. However, although most of the standards recommend decoupling frame and infill, practicable solutions for decoupling are not available. A possible realisation for the decoupling is the placement of a soft material between frame and infill in combination with steel profiles on both sides of the wall to provide an adequate out-of-plane resistance. However, this solution is not used in the construction practice, since the installation of additional steel profiles is too expensive and disrupts the application of plaster. Also Paulay and Priestley (1992) defined isolation of infill panels as one of the options to solve unfavourable interaction effects between infill wall and RC frame. They suggested to add a flexible strip between frame and panel, filled with a highly deformable material. Griffith (2008) pointed out that infill walls and especially partial-height infill walls often cause non-ductile shear failures in columns. Therefore he recommended a sufficient gap between the infill and the column. More recently Kuang and Wang (2014) and Jiang et al. (2015) proposed solutions for decoupling, but although the basic idea of these proposals is reasonable, the execution at site needs further modifications, especially to satisfy the sound and thermal insulation requirements.

Eurocode 8 (2004) describes in section §4.3.6 the three main classes of solutions introduced before, but just in a general form without giving any reasonable design approach. Therefore the traditional way to install masonry infills rigidly attached to the frame is still the most common application. Eurocode 8 (2004) prescribes in section §4.4.3.2 different limits of the inter-storey drift to prevent the damage of non-structural elements (here: infill walls) with 0.5%, 0.75% and 1.0% drift for the first, the second and third abovementioned classes of solutions. But because clear rules are missing, the recommendations are ignored in the daily practise and remaining gaps are still filled with mortar, polyurethane foam (Figure 2) or mineral wool. However, filling the gaps is usually not successful due to shrinkage, settlements and imprecise workmanship and also does not provide sufficient boundary conditions/connections for out-of-plane loading. Since the total elimination of the gaps is unrealistic, the effect of possible gaps on the resistance of the infills was studied by Liauw and Kwan (1984), who investigated the effect of small gaps which appear due to the shrinkage of infill material and concluded that such small gaps can cause a substantial reduction of the initial stiffness. Moghaddam and Dowling (1987) and Riddington (1984) confirmed a significant negative effect of small gaps on the structural behaviour of infilled framed systems. It can be summarized, that the unregulated situation and the questionable execution at site lead to a completely unknown safety level of masonry infills. Therefore reliable and simple solutions are needed.
3. EXPERIMENTAL INVESTIGATIONS

3.1 Test set-up

A test set-up has been specifically developed and constructed within the framework of the European project INSYSME (2016) by Kassel University to successfully carry out the in-plane and out-of-plane tests. The equipment and instrumentation of the test set-up is shown in Figure 3. At the beginning of all tests a vertical load of 200 kN per column was applied with two vertical cylinders simulating the vertical load from upper stories present in real buildings. The in-plane tests were performed through the application of increasing cyclic horizontal displacements with three cycles on each displacement level. For out-of-plane tests the loading perpendicular to the wall plane has been applied using four pneumatic pillows with a capacity limit of 50 kN/m². Forces and deformations of the hydraulic cylinders are recorded by the integrated displacement and force transducers. The force capacity of the two vertical hydraulic jacks amounts to ±400 kN each. The maximum stroke amounts to ±125 mm. For horizontal loading a cylinder with a maximum force capacity of ± 320 kN and a stroke limit of ±150 mm was used.

Figure 3. Test set-up for both in-plane and out-of-plane loading.
The forces and displacements of the hydraulic cylinders are measured with integrated displacements and force transducers. The horizontal and vertical displacements of the infill wall are recorded by up to nine inductive displacement transducers, which are fixed to the test frame to be independent from the infill wall. In addition, two potentiometers measure the displacements in the diagonal directions of the wall. The deformations of the infill itself are recorded by an optical measuring system, the measurements being carried out for a glued-on grid of measuring points. The optical system works with two cameras, so that the deformations in- and out-of-plane can be recorded simultaneously.

3.2 Experimental test campaign

Overall, four different systems were tested with regard to the load-bearing and deformation capacities of reinforced concrete frames with masonry infill walls of highly thermally insulated clay bricks. The tests were carried out by Kassel University in close cooperation with SDA engineering GmbH and Arbeitsgemeinschaft Mauerziegel im Bundesverband der Deutschen Ziegelindustrie e.V.. Table 1 presents the entire test programme involving in-plane loads, out-of-plane loads and combined in-plane and out-of-plane loads. The first step of the programme was to test a reinforced concrete frame without infill (System A) in order to determine the frame capacity. The “B” systems represent traditional masonry infills in which the masonry completely fills out the frame and is in direct contact with the columns and the beam. The effects of openings were simulated in these tests by leaving a gap between the infill wall and one of the columns. The “C” systems were performed on the innovative infill system IMES (Infill Masonry Enclosure System). In this system, special connecting elements are arranged between infill and frame to improve in-plane interaction behaviour. Finally, the “D” systems were performed on a newly developed system called INODIS (Innovative Decoupled Infill System), which is an advanced version of the IMES system with special U-shaped decoupling elements between the infill masonry and the RC frame. These elements prevent both, in-plane and out-of-plane failure of the infill. For this system, the tests were performed with in-plane, out-of-plane and combined loading applied to a one specimen. In the following the results of the innovative system INODIS are presented and compared to the behaviour of the traditional infills and the bare frame. The system INODIS itself will be described more detailed in the next section.

Table 1. Overview of test program with systems A-D.

<table>
<thead>
<tr>
<th>System</th>
<th>In-plane - Out-of-plane</th>
<th>Out-of-plane</th>
<th>In plane + Out-of-plane</th>
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<tbody>
<tr>
<td>A</td>
<td>Bare frame</td>
<td></td>
<td></td>
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<tr>
<td>B</td>
<td>Traditional</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>IMES</td>
<td></td>
<td></td>
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<tr>
<td>D</td>
<td>INODIS</td>
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4. PROPOSED SYSTEM

As already explained in Section 2, currently no masonry infill systems are available on the market, which are cost effective and fulfil the various requirements. Thus, within the European project INSYSME (2016) new innovative systems for the enhancement of the seismic resistance of masonry infill walls made of clay bricks were developed and analysed. The German partners developed two systems for improving the seismic behaviour of masonry infilled reinforced concrete frames. The purpose of both systems is to decouple frame and infill instead of improving the load-bearing capacity by means of expensive, supplementary reinforcing elements. In the following the performance of the final system INODIS system (Innovative Decoupled Infill System) is presented. The INODIS system (Figure 4) aims to raise the in- and out-of-plane resistance by means of dissipative and sliding connections along the circular contact areas of the infill to the reinforced concrete frame. The system decouples the infill wall and reinforced concrete frame with U-shaped elastomeric bearings at the top, bottom and along the vertical edges. The bearings are designed to allow the design drift of the reinforced concrete frame without inducing damages to the infill wall. Furthermore the viscoelastic bearings enhance the overall damping capacity of the building. The deformation capacity of the elastomer is chosen according to the design needs in order to separate the infill wall from imposed in-plane deformations of the concrete frame. Plastic profiles are attached by screws to the surrounding frame while elastomeric bearings are glued to the masonry infill on one side and placed around plastic profiles on the other side, thus preventing the out-of-plane failure. Figure 4 shows the arrangement of the system with the connection details.

![Diagram of the INODIS system](image)

Figure 4. Sketch and photos of the installed system INODIS: a) front view of the infilled frame; b) side view cross section; c) installed U-shaped elastomer between column and infill; d) horizontal cross section; e) attaching plastic profiles to the frame; f) installation of U-shaped elastomer; g) MZ 70 clay brick.

5. LOAD PROTOCOLS

The traditional infill system was tested using three specimens. The specimen denoted as a BI was loaded just in-plane up to a level of 1.25% (34.4 mm) of drift, then just in out-of-plane direction and then again just in-plane up to failure. The specimen denoted as a BO was loaded just in out-of-plane direction up to the failure. In order to account for unfavourable effects due to openings (e.g. doors or windows), an air gap has been left between one column of the frame and the masonry infill. The BIO specimen corresponds to the specimen for BI test, but it was loaded first with the out-of-plane pressure...
of 5kN/m² which was then kept constant during simultaneous application of in-plane displacements (Figure 5, left). The INODIS system was tested with a complex loading protocol (in-plane, out-of-plane and simultaneous in-plane and out-of-plane). The whole loading protocol was carried out with one specimen, which is denoted as DIO. The overall loading protocol can be divided in seven phases as described in Table 2 and shown in Figure 5, right.

Table 2. Detailed load protocol of test DIO.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Description</th>
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<tbody>
<tr>
<td>Phase 1</td>
<td>IP up to 1.25% of drift (34.38mm)</td>
</tr>
<tr>
<td>Phase 2</td>
<td>OOP up to 5kN/m² (34.5kN)</td>
</tr>
<tr>
<td>Phase 3</td>
<td>Simultaneous loading - 1.5kN/m² (10.4kN) OOP load and up to 1.0% (27.5mm) IP drift</td>
</tr>
<tr>
<td>Phase 4</td>
<td>Simultaneous loading - 5kN/m² (34.5kN) OOP load and up to 0.5% (13.75mm) IP drift</td>
</tr>
<tr>
<td>Phase 5</td>
<td>Simultaneous loading - IP drift rising 0.6% up to 1.8% (49.5mm) and 2.5-5kN/m² OOP load (changing each two in-plane amplitudes, first 2.5kN/m² (17.3kN) then 5kN/m² (34.5kN))</td>
</tr>
<tr>
<td>Phase 6</td>
<td>Simultaneous loading - IP drift of 1.0% (27.5mm) and 6.25kN/m² (38kN) OOP load</td>
</tr>
<tr>
<td>Phase 7</td>
<td>Simultaneous loading – IP drift rising from 1.0% up to 3.25% (89.4mm) and 1.5kN/m² (10.4kN) OOP load</td>
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Figure 5. Loading protocols of the tests BIO (left) and DIO (right)

6. EXPERIMENTAL RESULTS

The effectiveness of the system INODIS is demonstrated by a comparison with the traditional infill and the bare frame. The comparison of the hysteretic curves of the different systems and load combinations (Figure 6, left) shows clearly the advantage of the INODIS system with a high deformation capacity and low activation of horizontal forces similar to the bare frame. It has to be pointed out, that the in-plane response of the system DIO was obtained applying the whole load protocol including prior and simultaneous out-of-plane loading. Furthermore, different to the system configuration B the in-plane capacity of the DIO specimen was not reached due to the limitation of maximum drift of the experimental set-up. Figure 6 (right) shows the envelopes of the hysteresis loops for each of the systems. Moreover, the cyclic response has been evaluated as the difference between the responses of the infilled frame and the bare frame. This allows a consistent comparison of the experimental data in terms of maximum load, stiffness and deformation capacity.

Figure 6. In-plane hystereses (left) and envelopes and contributions for the systems A, B and D (right).
Figure 6 shows that the INODIS system is able to withstand a 1.3 times higher horizontal force than the bare frame (A: 120kN / DIO: 155kN). In both tests, the restoring force increases steadily until reaching the maximum value and the hystereses loops are quite similar. A comparison of the in-plane behaviour with the traditional system configuration BI shows remarkable differences with respect to the initial stiffness, maximum load and drifts. The system INODIS is activated slowly with a low stiffness and the load displacement curve is smoothly rising up without a sudden drop down as in a case of system BI. The comparison of the infill contributions clarifies, that the contribution of the INODIS system is more than three times smaller. The highly reduced contribution leads to a behaviour quite close to the bare frame, especially within the recommended drift ranges in Eurocode 8 (2004).

Another finding of utmost importance is the improvement of the attainable maximum drift levels. First cracks occur for system BI at 0.3% (8.25 mm) and for system DIO at 1.8% (49.5 mm) drift and ultimate drift levels reached are 1.9% (52.5 mm) for system BI and 3.25% (89.4 mm) for system DIO. Again it has to keep in mind that the excellent in-plane results for DIO were obtained with just one specimen applying in-plane and out-of-plane loading as well as simultaneous loading conditions. The functioning of the system DIO is shown in Figure 9 with compression of the elastomer and formation of a gap under reverse loading. In a case of simultaneously loading the behaviour of the system DIO is compared to the system BIO. When compared to the BO specimen (loaded just in out-of-plane direction) BIO specimen (loaded simultaneously) shows a reduction of the maximum out-of-plane capacity around 12.5%, while reaching just 1% (27.5 mm) of in-plane drift. Not only the reduction of the resistance is critical, but also the BIO specimen experienced high deformation in out-of-plane direction with pronounced tilting of the wall (Figure 7). The whole system becomes quickly unstable and is no longer safe. Finally some short notes are summarized for the traditional system configuration BI. The experimental tests on specimen BI clarify, that the after first in-plane loading phase damage of the mortar connection between top row of the infill and beam take part. This fact will definitively reduce the formation of the arching effect in out-of-plane direction, thus a substantial reduction of the out-of-plane capacity will take place. The INODIS system configuration (DIO specimen) shows a much better performances reaching 1.8% (49.5 mm) of in-plane displacement with simultaneously applied 5kN/m² of out-of-plane pressure without any damage (Figure 8). At the same loading conditions specimen BIO starts to experience damage already at small drifts of about 0.4% (11 mm) and at the drift of 1.0% (27.5 mm) the ultimate limit is reached. In contrast, specimen DIO reached 3.25% (89.4 mm) of in-plane drift, even with simultaneously applied out-of-plane pressure. Furthermore the DIO configuration shows a reduction of the out-of-plane displacements and stable support conditions because of the special U-shape elastomers combined with plastic profiles. As expected the maximum deformation takes part in the middle of the infill (Figure 8). Damage of the DIO system takes place at drifts beyond 1.8% (49.5 mm). The damage is characterized by bending tensile strength failure caused by the activation of arching mechanism. Along the circumferential supporting RC frame, only small out-of-plane deformations are visible and the connecting bricks are apparently intact, although the highly thermally insulated clay blocks are quite sensitive to local failures.

![Figure 7. Out-of-plane displacements of the traditional infill wall (BIO specimen) under simultaneous loading](image-url)
7. SIMULATION RESULTS

Results of the experimental tests were used for calibration and validation of the numerical models, developed on micro and macro level. In order to investigate the global response of structures with masonry infill walls the model developed by Crisafulli (1997) is applied to the masonry infills at the macro level. This model can describe not only the material behaviour under monotonic loads, but also the hysteresis behaviour under cyclical loads. Smyrou (2006) implemented this model into the Seismostruct programme (Seismosoft 2016). This model allows the simulation on structural level with a reduced computational effort and satisfactory accuracy. Micro models are used for modelling of single RC frames with masonry infills to study the specific failure modes of the infill and frame and to simulate the behaviour of the installed innovative connections. For micro-modelling, the software package Abaqus (ABAQUS 2012) was used, where the model consists of three dimensional solid elements for concrete, clay bricks and beam elements to represent the reinforcing bars. The reinforcement is modelled with truss elements using an isotropic elastoplastic material formulation. Reinforcement and concrete are coupled by means of an embedment of the truss elements within the solid elements. Although a detailed three-dimensional numerical model is used, slight simplifications are useful in order to perform a comprehensive parametric analysis. Since the masonry consists of bricks and mortar joints, this results in anisotropic behaviour of the wall. This is considered by modelling the bricks and mortar joints separately and by defining interaction between them. The concrete and the clay blocks are modelled using a plastic-damage material model, which includes isotropic hardening. For further details about the modelling approach reference is made to Butenweg et al. (2016, 2017) and Kubalski et al. (2016, 2017). Figure 10 presents a comparison of load-displacement curves for bare frame and traditional infill under in-plane loading. The simulated curves...
show a satisfactory agreement with the experimental results for both micro and macro models. Figure 11 shows comparison of simulation and experimental results obtained with the micro model for bare frame, traditional infill and infilled frame with innovative system under in-plane loading up to really high in-plane drifts. Again it can be concluded, that the INODIS system postpones the infill damage and pushes ultimate drifts to high levels.

Figure 10. Comparison of curves for in-plane loaded bare frame (left) and traditional infill (right)

Figure 11. Comparison between simulation and experimental results: bare frame, traditional infill and innovative infilled frame system

The work so far was mostly focused on calibration and validation of numerical models, but in the next period both models will be used for parametric studies on different geometries of the frame and infill components, thicknesses of the elastomeric connections, material characteristic etc. It is intended to use the results of the parametric studies to derive simple design rules for everyday practice.

8. CONCLUSION

The present paper has focused on presenting an innovative system for masonry infilled RC frames called INODIS. Experimental studies are presented to demonstrate the effectiveness of the developed system. The innovative system decouples the infill wall and reinforced concrete frame by the use of elastomeric bearings at the top, bottom and along the vertical edges. The bearings are glued to the infill wall and with its U-shape placed around plastic profiles which are attached to the surrounding frame. Basic idea of the system is to allow the design drift of the reinforced concrete frame without inducing damages to the infill wall and at the same time to give a reliable support to out-of-plane resistance. Furthermore the viscoelastic bearings will enhance the overall damping capacity of the building. The comparison of the innovative system with traditional approaches shows several benefits of the system: Adequate seismic resistance for simultaneously acting in- and out-of-plane loads; Reduction of the stresses within the infill; Prevention of unfavourable interactions; Transformation of the infill to a real non-structural component; Reduction of the seismic action by means of distributed
energy dissipation. Additional advantages are the cost effectiveness, the simple installation and the beneficial effects on the sound isolation. The experimental tests were carried out by Kassel University and financial support was given by Arbeitsgemeinschaft Mauerziegel im Bundesverband der Deutschen Ziegelindustrie e.V., which was also involved in the system development. The system INODIS is already patented on European level and will be further developed for market introduction.

9. ACKNOWLEDGMENTS

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