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Reduction of stress concentration by polymer flexible joints in seismic protection of masonry infill walls in RC frames

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Abstract. In the paper, the phenomenon of stress concentration occurring in brittle structural materials of infill structures is discussed. Four innovative repair methods based on flexible joints made of polyurethane PM are presented. They provide a reduction of the stress concentration and improvethe structural ductility. The effectiveness of newly proposed timber-polyurethane dissipative struts is proved by laboratory shear tests, which results are discussed in detail. The calculated dissipation energy and stiffness of the proposed system ensures a simultaneous transfer of loads and large deformations occurring during an earthquake to the introduced dissipative struts and improves the system safety. The recommended repair methods can be used efficiently by emergency teams in seismic areas.

1. Introduction

1.1. Masonry infills' behavior during an earthquake

Reinforced concrete (RC) frames' masonry infills are very popular structures in civil engineering, as constructions resistant to earthquakes. Anyway, they are vulnerable to large deformations, because stiff infills are rigidly connected to the RC frames. The infills contribute to lateral stiffness as well as the resistance of such construction systems,but are vulnerable to cyclic loads and crack easily during seismic excitation under stress concentrations generated by moving frames. Tensile stress initiates diagonal cracks and compression stress in corners causes crushing of masonry infills (figure1a) or even destroying of RC columns, what was presented in detail in [1-4]. Such cracked masonry panels may be very dangerous during aftershocks, because they may not be very well fixed to the framed structure as well as cohesion between defragmented masonry parts may be very low. This implies high costs and risks forinhabitants, state, and society because people are threatened by out-of-plane failure modes (figure 2). To protect such weakened structural elements, new innovative repair methods using flexible joints are proposed [5], which use flexible polyurethanes (PM polymer) – figure 1a.

1.2. Stiffness related to stress concentration

Currently, most common building materials transferring loads as concrete and masonry are characterized by relatively high stiffness (with the elastic modulusexceeding 1 GPa) and brittle behavior, in comparison to polyurethane joints, which elasticmodulus ranges from2 to 40 MPa. Taking into consideration large-scale structural elements carrying loads, like walls, beams, slabs or columns, high stiffness is an advantageous property because it allows constraining deflections (infill walls). On the other hand, high rigidity is accompanied by brittleness, manifested by a sudden failure of structural material (without warning). Results of large-scale compressive stress concentration are presented in figure 3, where crushing of corners in concrete pavement is caused by thermal elongation and "soft story" effect [6] initiated by infill strut. If the safety of users is required, this kind of behavior is preferably avoided in structural elements, especially in seismic areas, where ductile behavior is needed.

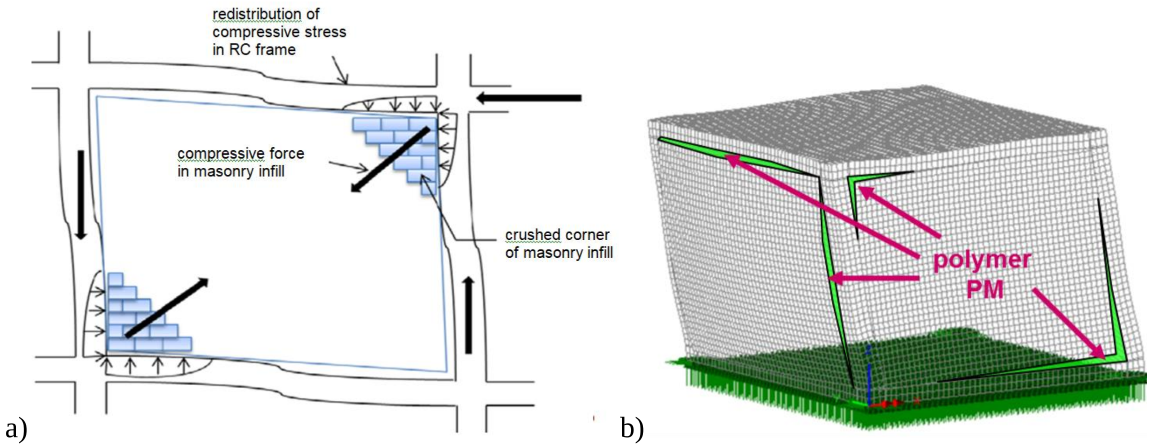

Figure 1. Infills behavior under large deformation: stiffly connected to RC frame (a), bonded to RC frame using flexible joint made of PM polyurethane(b).

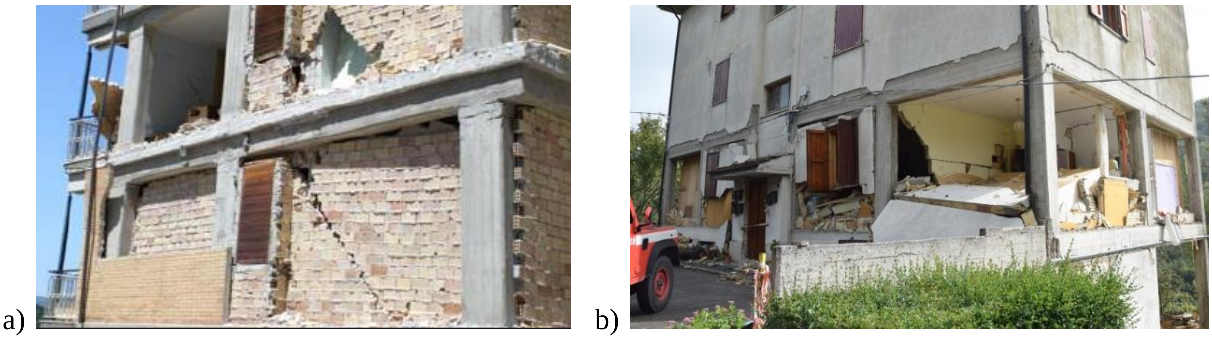

Figure 2. Examples of infill failure: cracking and corner crushing (a), out-of-plane movement (b).

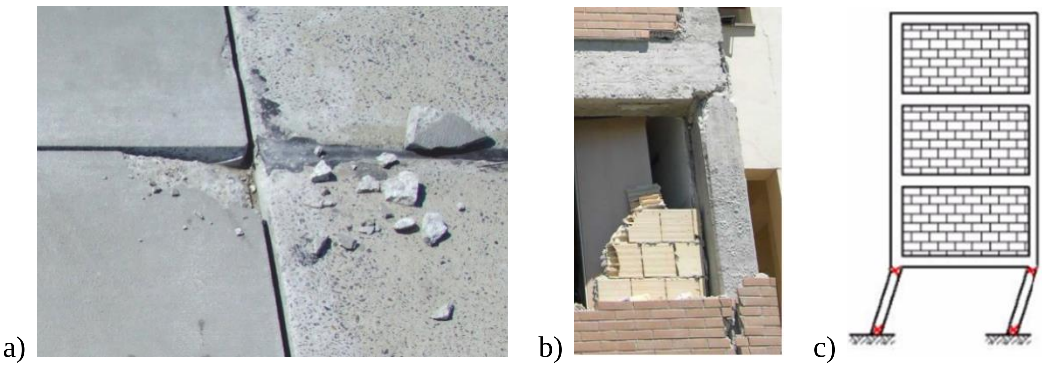

Figure 3. Examples of infill failure: concrete corner crushing in the pavement (a), RC column damaged by infill strut generating compressive stress concentration (b), "soft story" effect (c).

Focusing on the microscale behavior of concrete and masonry, the matrices of these materials include structural discontinuities (e.g., at an interface between gravel and mortar in concrete), being triggers of strain and stress concentrations when the material is loaded. Peaks of stress concentrations overcome the material strength with the increased load, forming microcracks, some of which get coalesced and propagated into the main crack. The rest of microcracks make the brittle material weaker in the vicinity ofnewly-formed cracks. In brittle materials, cracks develop and propagate, causing failure of structural elements. This is the reason why materials have to be protected against crack propagation and repaired [5].

1.3. Stiff and flexible repair injection

One of the repair methods is crack-filling using bonding materials (injection), which join cracks' sides, stopping their development. Various stiff bonding agents such as epoxy resins or cement-based fluids (with elastic modulus of 4-30 GPa and elastic properties) are used. Stiff inject bonds the crack, but microcracks in its surrounding are developing under stress concentration with reloading of the structure, creating a new rapidly propagating main crack even at the load level lower than the primary one. In such cases, the repair using stiff bonding agents failsto improve or even recover the initial strength of the cracked structure, because it fails to reduce peaks of stress concentration [7].

An innovative solution tothe external repair is usage of flexible bonding agents for crack-filling, which stiffness is much lower than that of the bonded structural material. Moreover, these flexible materials can withstand high deformations and are non-elastic, resulting in a reduction of stress concentration factor and stress redistribution. Such properties of the flexible repair bond allow for increasing the load-bearing capacity of cracked structural components made of brittle materials [5, 7]. The application conditions are quite strict (e.g., no dust, temperature over 5°C, etc.) and should be satisfied to ensure the above strength improvement.

2. Repair intervention in infill systems using flexible joints

2.1. Repair injection using polyurethane PM

As deformable injection material filling cracks in damaged masonry infills, flexible polyurethane Sika PM (with patented additives) is used. It is characterized by the following properties [1]: elastic modulus of 4.5MPa, tensile strength of 0.85÷1.95MPa, ultimate strain of 50÷150% (depending on the loading rate). This material was tested in many practical applications for full-scale structural elements and manifested itshigh efficiency [8].

Masonry infills are cracked in the in-and out-of-plane modes (figure 4a,b,c), causing the loss of stiffness resistance. In the location of cracks, stress concentrations are generated by earthquake-induced large deformation, causing further degradation. Repairs using stiff injection (cementitious mortar, epoxy resin) do not increase the ductility, which is required in seismic areas. On the contrary, the injection with polyurethane PM (figure 4c) allows to recover the in- and out-of-plane resistances, as well as significantly contribute to the ductility.

Flexible polyurethane can also be used as protection of infills and RC frames against stress concentration at the interface [1] in existing buildings. The space at the interface can be cut (1-3 cm-thick) and filled with Sika PM (figure 4d). In case o seismic excitation, local stress concentration (generated by the infill strut - figure 1a) is reduced by redistribution over a larger area. Moreover, ore ductile behavior of the whole system is introduced (figure 1b). When this kind of wall is damaged by a strong excitation, cracks can be repaired by polyurethane PM injection (figure 4e, f).

In newly-constructed buildings, a flexible joint can be made as a prefabricated layer of Sika PM. This layer is bonded at the inner surface of the RC frame, and next, masonry infill is erected (figure 5a). Properties of such system are very similar to the presented one, dedicated to existing buildings (figure 4d). Similarly to the previous case, a cracked wall damaged by a shock can be repaired by polyurethane PM injection (figure 5b,c). The efficiency of such a flexible interface solution was manifested in full-scale cyclic laboratory tests [1].

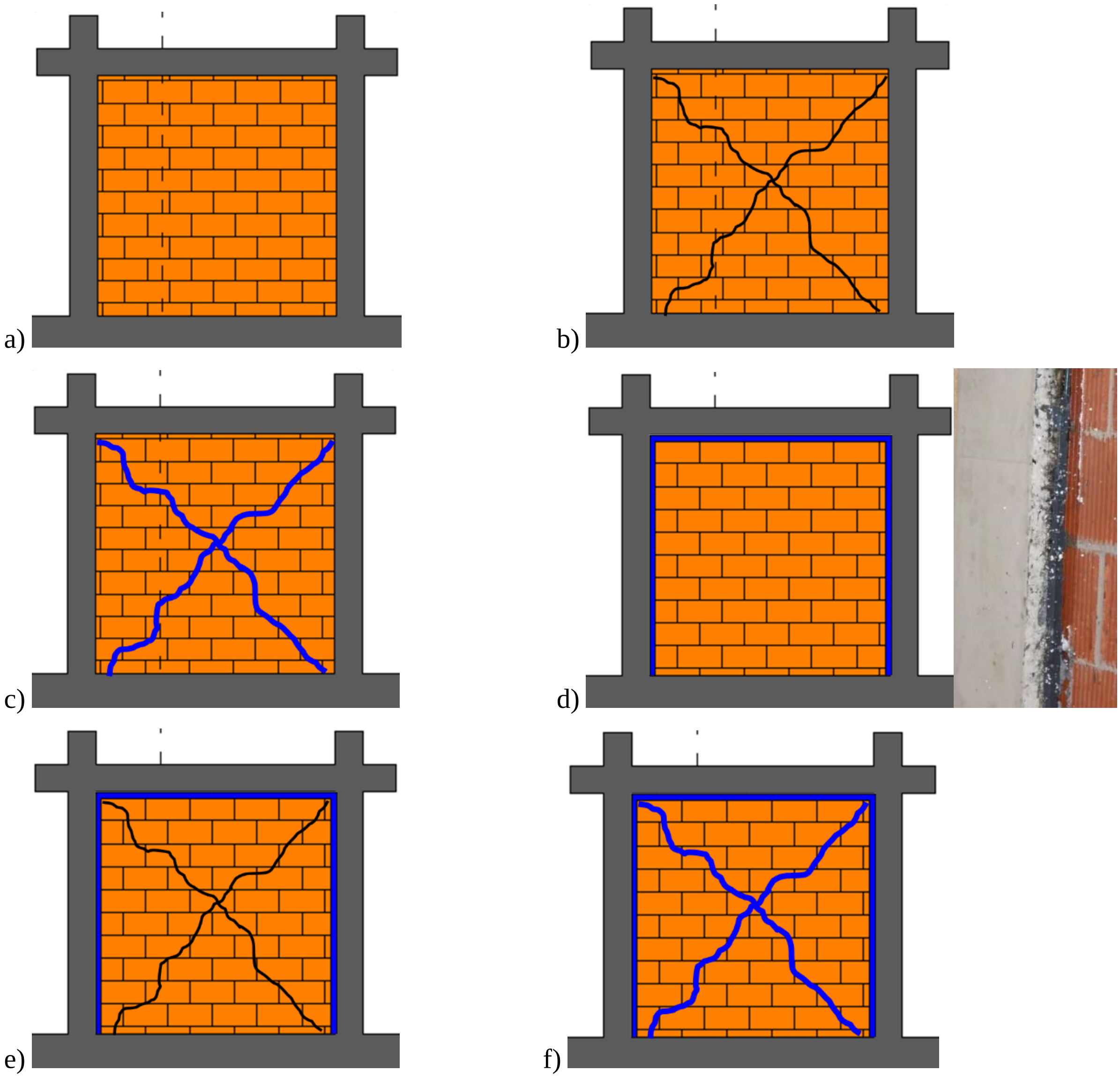

Figure 4. Infill walls with a stiff classical interface (a): cracked (b) and repaired by PM (c), and with flexible PM interface(photo of joint) in the existing building (d): cracked (e) and repaired by PM (f).

2.2. Emergency protection of "soft story."
Stress concentration causes cracks of infills and damages of RC columns in the shear mode (figure 3b). When infills collapse in out-of-plane mode (figure 2b), hinges are generated on both ends of damaged columns by inertial forces and initiate dangerous “soft story” effect (figure 3c). To protect the whole structure immediately against loss of stability and collapse, because of lack of shear resistance in empty RC frame (figure 5d), a new timber strut resistor with dissipative flexible joints is proposed. It consists of timber elements (with wood grainsparallel to the load) bonded together with polyurethane PM joints, working in two variants (figure 5e, f). Generally, the dissipative timber strut prevents horizontal movement of the upper frame part, blocking deformation at the compressive diagonal of the framein a visco-elasto-plastic manner. Energy is dissipated in both variants by shear deformation of the Sika PM joints. Extra dissipation is given by locking elements in the frame corners, fixed to the strut ends. In the first variant (figure 5e), extra dissipation assures deformation of the locking elements made of soft timber with wood grains perpendicular to the compressive load. In the second variant (figure 5f), the locking elements are made of polyurethane PM.

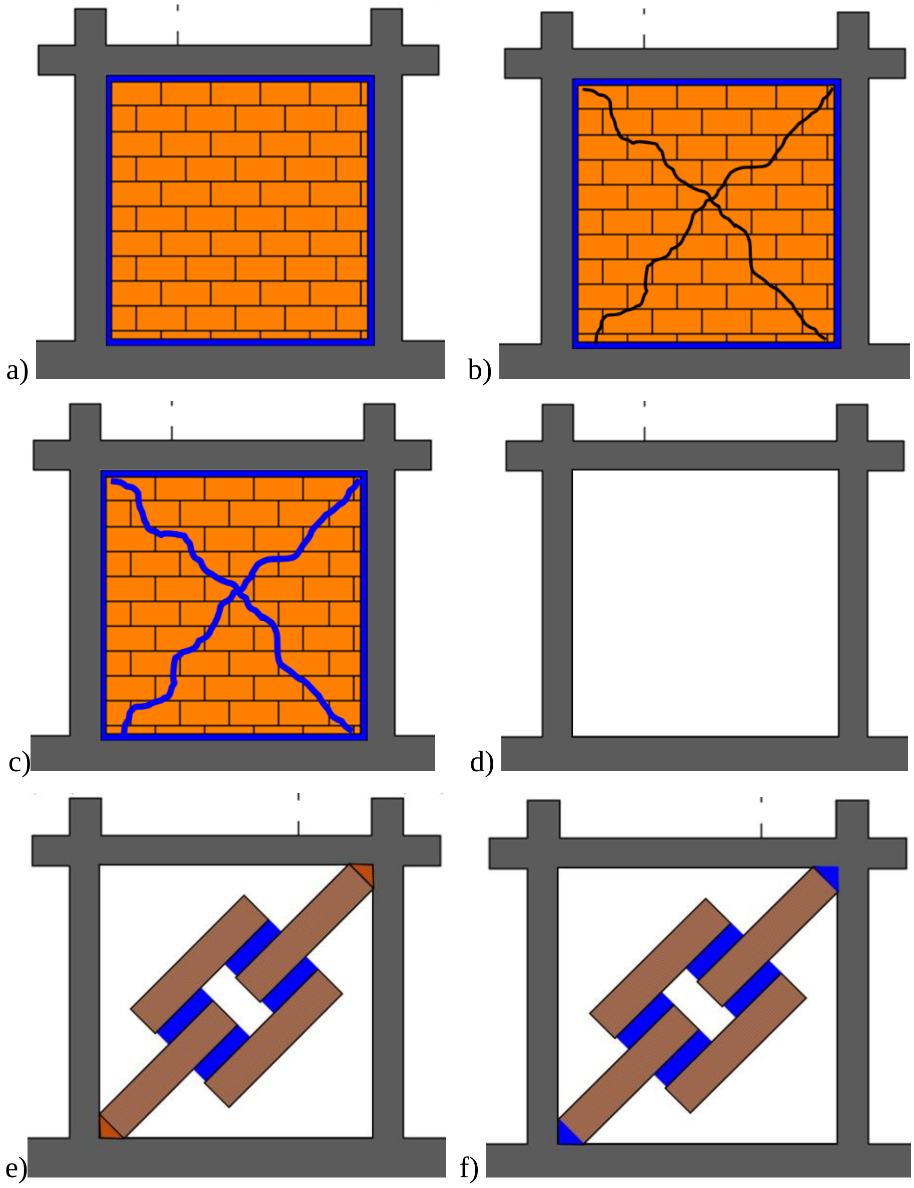

Figure 5. Newly-constructed infill with flexible PM interface (a): cracked (b) and repaired by PM (c); and "soft story" (d), protected by dissipative struts with ends made of soft wood (e) and PM (f).

2.3. Dissipation energy by timber elements and flexible joints

Innovative dissipation properties of the timber-polyurethane system were discovered during research in a project carried out by PalettenWerk on new wooden houses with flexible polymer joints, replacing steel dowels [9]. During shear tests of timber-polyurethane PM connections (figure 6), visco-elastoplastic deformation of PM joints and timber elements made of spruce class C24 (joint thickness 3 mm, bonding area 2x100x136 mm) was observed (figure 6b). Even after the damage of the polyurethane joint, residual resistance of the joint was observed (figure 6c and 7a,b,c). The representative element (one from 36 tested) dissipated the energy of 456 J (figure7a) during deformation, whereas the PM joint consumed only 130 J (figure 7b). The shear modulus of the connection (measured in the range of elastic behavior – figure 7c) was G = 1.15 MPa, which corresponded to the stiffness K = 88 kN/mm per 1 running meter of the flexible joint presented in figure 7d, when a horizontal load was applied tothe house designed by PalettenWerk. This example confirms significant dissipation and load-carrying abilities of the system.

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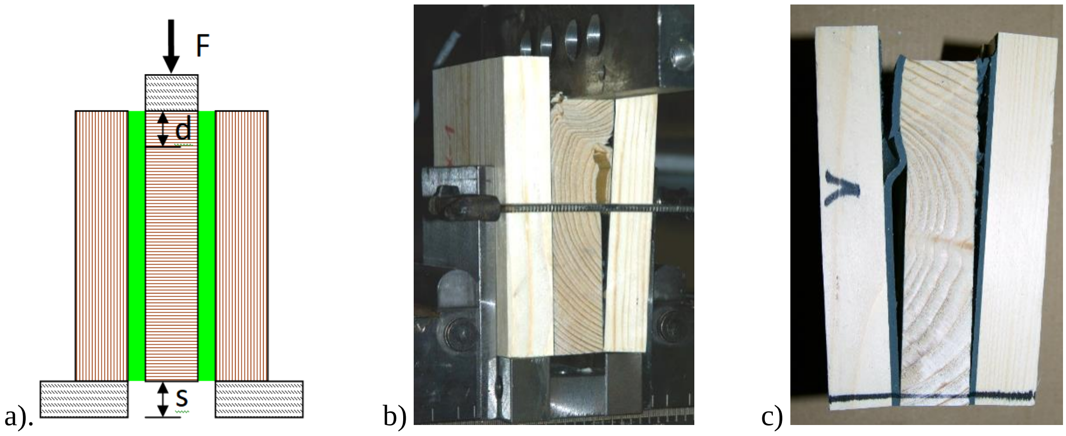

Figure 6. Shear test of PM joint between timber elements: setup (a), deformation of the specimen during the test (b), failure mode with visible permanent deformation of the inner element (c).

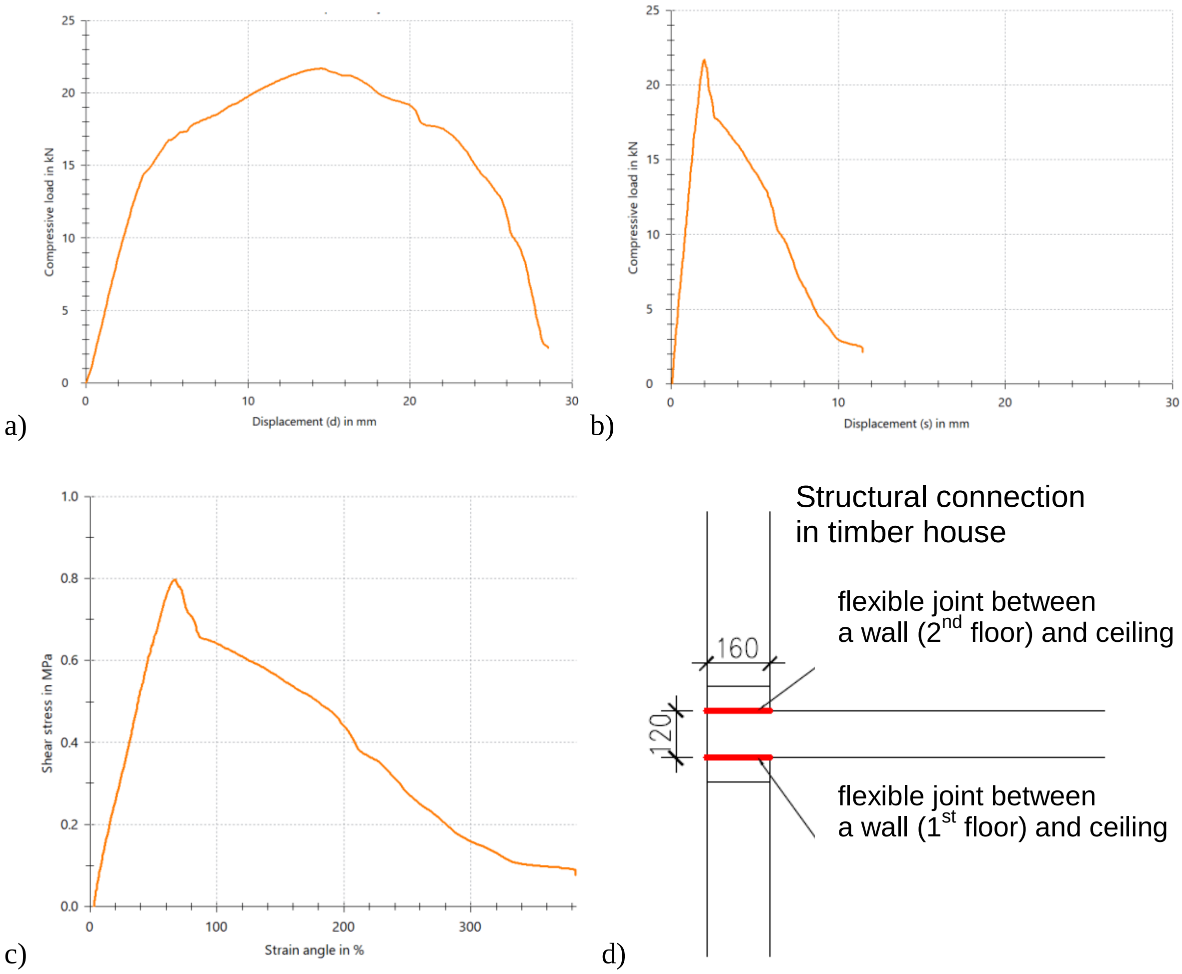

Figure 7. Test results: load vs. displacement of top surface “d” (a), load vs. displacement of bottom surface “s” (b), shear stress vs. strain angle (c); and structural connection using flexible joints (d).

3. Conclusions

The reduction of stress concentration by polymer flexible joints in seismic protection of masonry infill walls in RC frames was presented in 4ways, using polyurethane Sika PM, which reduced stress concentration and provided a significant stress redistributionin brittle materials (concrete, masonry), due to its high deformability and load-carrying capacity. The first method is based on PM injection, applied to cracks with damaged infills, recovering their load-bearing capacity and introducing higher ductility in them. The second one protects the existing infills against stress concentration and damage by creating a flexible interface in the space cut between infills and RC frames. The third one is a modification of the second method, as applied to newly-constructed buildings. The last proposal protects RC frames of "soft story" by using dissipative timber struts equipped with flexible joints made of polyurethane PM.

The first three methods use the innovative approach in civil engineering, in which highly deformable polyurethanes improve the load-carrying capacity and ductility ofrepaired structures, which were damaged during earthquakes, and assure a safe operation of infillstructures during aftershocks and further earthquakes. The fourth emergency method uses visco-elastoplastic properties of a new timber-polyurethane system for dissipating the deformation energy and protecting the “soft story" against collapse, by bearing the compressive load when inertial forces act during an earthquake. Additionally, locking elements of the strut ends with flexible timber elements (which grains are normal to the compressive load direction) or with PM ones, introduce extra dissipation abilities. Such a strut system is rapidly erectedand, thus, can be used by emergency teams in post-earthquake areas for the fast protection of damaged buildings against collapse in the expected aftershock. Advantageous properties of this system were confirmed by laboratory tests in the frame of the PalettenWerk project.

Acknowledgments

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