16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 4347 (Abstract ID)

Registration Code: S-P1464613144

A RUBBER-BASED SYSTEM FOR DAMAGE REDUCTION IN INFILL MASONRY WALLS

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Abstract

Post-earthquake examination reports of damaged buildings have identified that losses due to damage of the non-structural elements can exceed those from the structural damage.

The paper describes an innovative composite rubber/masonry infill for minimizing earthquake damage to the masonry as well as controlling the seismic performance of the R.C. moment resisting structures by offering auxiliary energy dissipating capability to the building. The composite rubber/masonry infill is therefore capable of interacting in an efficient and controllable way with the reinforced concrete frame, thus optimising a combination of strength, deformability and energy dissipation capacity in three orthogonal directions from the rubber device.

The use of a specially shaped rubber joint in the construction of masonry wall minimizes the seismic damage to the partition and infill at a desired performance level and reduces the seismic demand from the reinforced concrete structures by providing auxiliary energy dissipation. Design of the innovative rubber joint capable of providing widely different stiffnesses along the three orthogonal directions is presented.

The innovative rubber joints were designed and manufactured at TARRC and were provided for laboratory tests of confined masonry walls within the INSYSME project funded under the 7th Framework Programme of the European Commission [5]. Some important conclusions from the laboratory tests are presented.

The innovative system requires only simple technology and therefore is applicable of not only to modern structures but also to low-cost construction prevalent in low income seismic areas of the world. The innovative joint received positive feedback from the Italian masonry construction profession in installing the joints within masonry walls.

Keywords: masonry infill; in-plane damage; rubber joint; damage control, arch mechanism; dissipation

1. Introduction

A large body of published papers have examined the contribution of masonry infill to the response of reinforced concrete (RC) frame structures during an earthquake. However, the common practice is to ignore the infill walls' contribution during the design phase resulting in the structural response deviating significantly from the predictions. The general assumption that masonry infill does not play a role in the dynamic response of the structure during a seismic event has now been recognised not to be the case.

The experience of the 2009 earthquake in L'Aquila, Italy has shown that the reinforced concrete structures responded reasonably well to the severe level of ground motion. However, there was a significant level of damage to confined masonry infills and partition walls [1]. This amounted to 35% of the RC frame structures inspected after the earthquake. Similarly, in-plane, out-of-plane or combined damage to confined masonry infill was observed after the May 2012 Emilia Romagna earthquake in Italy [2].

The most important post-earthquake evidence observed in the above cited examples as well as in other countries with different construction traditions and technologies has shown that out-of-plane collapses occur at the lower stories. This is where the in-plane damage mainly occurs due to high base shear but the out-of-plane forces are the lowest in the building, whilst at upper stories, where the out-of-plane forces are the highest, in-plane damage and out-of-plane collapse are not observed. These observations seem to confirm that the provision of ductility in the structure offers a predictable and safe response but can result in subjecting the confined masonry walls to significant in-plane deformation and subsequent out-of-plane collapse during the seismic event.

The most popular approach has been to prevent in-plane damaged infills from undergoing out-of-plane collapse during the seismic event and consequent danger to people and major economic losses. Allowing in-plane damage has the disadvantage that the evolution of in-plane damages during an earthquake produces complex and uncontrollable dynamic behaviour, as the collapse of infill panels appears to be completely random. In addition, the progressive deterioration of the panels, occurs mainly in the lower floors. This in turn produces "soft storey" type behaviour which is prohibited by seismic codes throughout the world.

The purpose of this paper is to present an innovative composite rubber/masonry infill which solves the problem of out-of-plane collapse, in a different and much more efficient way, by preventing in-plane damages to infills and partitions during the earthquake i.e. the main cause of out-of-plane collapse. Another significant attribute of the proposed solution is in controlling the seismic performance of the RC moment resisting structures by offering auxiliary energy dissipating capability to the building. The composite rubber/masonry infill is therefore capable of interacting in an efficient and controllable way with reinforced concrete frame, thus optimising a combination of strength, deformability and energy dissipation capacity in three orthogonal directions from the rubber device. It may therefore be possible to design RC frames, partitions and infills in such a way that their combined behaviour is optimised in terms of:

- minimising the seismic damage to the partitions and infill at a desired performance level;
- reducing the seismic demand from the RC structures by providing auxiliary energy dissipative elements;
- improving performance of existing RC frames, before or after a seismic event;
- minimising the building's cost of the construction and its life-cycle cost.

2. Innovative composite rubber/masonry wall

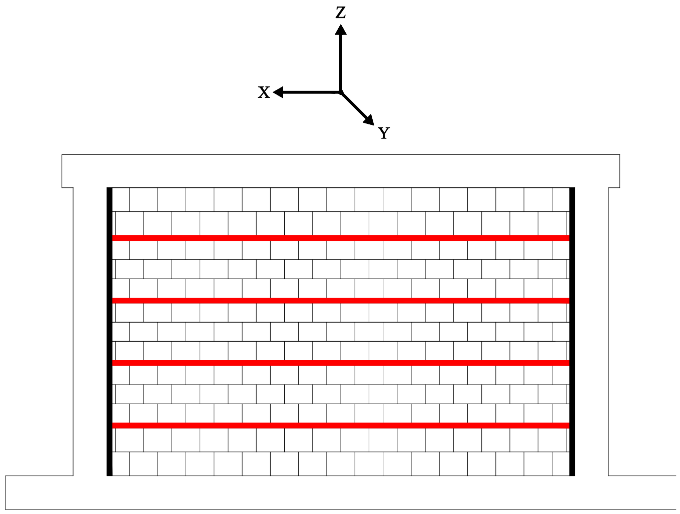

Fig. 1 – Composite rubber/masonry wall within reinforced concrete frame. The horizontal rubber joints are shown in red and vertical joints are in black.

The rubber/masonry composite wall, shown in Fig. 1, provides seismic protection by utilising three mechanisms. These are:

2.1 In-plane damage control

During the seismic event the reinforced concrete frame structure deflects sideways in the plane of the wall and exerts a resultant force, parallel to the diagonal of the frame, on the bricks of the masonry infill. These forces can either crush the bricks or crack the mortar. Layers of rubber are inserted between rows of bricks as shown in red in Fig. 1. These horizontal rubber joints deform in shear, allowing rows of brick to move horizontally relative to each other in the plane of the wall, thereby reducing the stress in the bricks as the RC frame structure sways during the seismic event. In addition, thin sheets of rubber, shown in black in Fig. 1, can be placed vertically at the interface between the columns of the RC frame and the brick wall to control the forces exerted on the bricks. The compressive stiffness of the vertical sheet of rubber controls the amount of the force transmitted to the bricks. If the compressive stiffness is sufficiently low no damage is experienced by the bricks.

2.2 Out-of-plane containment by invoking arch mechanism

The formation of an arch during out-of-plane deformation of a masonry wall, confined within a RC frame is well known [3] and is addressed in European Code 6 [4]. The arching profile is generated due to the rotation of the masonry bricks within the wall. As the masonry wall is constrained within the RC frame the rotation of the bricks leads to the generation of a clamping force which will tend to hold the bricks in position and resist their rotation. The clamping force needs to be sufficient to restrict the out-of-plane motion and hence prevent collapse. However, a very high clamping force will result in crushing of the masonry bricks due to high localised contact stresses, which will relieve the force and may lead to bricks popping out of the wall.

A rubber sheet, which is stiff in compression, placed horizontally between the rows of the bricks, enables the generation of sufficiently high clamping force but spreads it over a wider area so that the contact stresses do not reach the crushing threshold for the bricks. A further requirement of the sheet is to have a high enough stiffness in shear in the out-of-plane direction of the wall to prevent the bricks from sliding out of the wall.

2.3 Energy dissipation to control the response of the structure

The compressive stiffness of the vertical sheet of rubber can be optimised so that sufficient force is transmitted to the rows of bricks to move them over the horizontal joints, mentioned in Section 2.1. The horizontal cyclic translation of the bricks during the earthquake results in the shear deformation of the horizontal joints. Optimisation of the shear stiffness of the horizontal joints and the compressive stiffness of the vertical joints can be used to not only eliminate or control damage in the bricks but also to maximise the dissipated energy through cyclic shear deformation of the horizontal joints. This will increase the damping of the structure and therefore reduce the global response of the structure which in turn reduces the demand from the structure as well as the wall.

2.4 The force-deformation characteristics of the horizontal rubber joints

As outlined in the preceding paragraphs, the horizontal rubber joint requires different stiffnesses in the three orthogonal directions of the wall. The shear stiffness of the joint along the x-direction (see Fig. 1), k_x, should be low enough to accommodate the in-plane motion of the frame and the wall. However, to provide sufficient clamping force to maintain an arched out-of-plane deformation the stiffness of the joint through its thickness, k_z, should be more than two orders of magnitude higher than k_x. In addition, the joint should have high enough stiffness in shear across its width, k_y, to prevent the blocks from sliding out of the wall. Therefore, the anisotropic stiffness relationship of $k_z>k_y>k_x$ is required from the horizontal joints.

3. Design of the horizontal joint profile

3.1 Stiffness characteristics

The stiffness requirements were calculated by the University of Padua, in the framework of the EC-funded project INSYSME, [5] and are given in Table 1. In order to fit within a preconceived size of frame and masonry structure each joint was required to have a maximum height of 30 mm. The thickness of the wall was 300 mm.

Table 1 – Stiffness requirements of joint per metre length of wall

Direction	Axis	Stiffness requirement kN/mm/m
vertical	Z	> 3750
horizontal out-of-plane	Y	> 20
horizontal in-plane	X	< 8.5

The vertical stiffness per unit length may be estimated from the formula for a bonded plane-strain layer [6]:

$$k_z = \frac{4GB}{t}\left(1+S^2\right) \tag{1}$$

where G is the shear modulus of the rubber, B is the width of the layer (thickness of the wall) and t is the thickness of the layer. Assuming a flat profile in the in-plane direction, the in-plane horizontal stiffness per unit length may be estimated by assuming a simple shear deformation:

$$k_x = \frac{GB}{t} \tag{2}$$

These equations were used to estimate the stiffness of various candidate designs. Plane strain FEA simulations of the most promising profiles were then carried out using Abaqus Standard v6.10. The rubber was modelled as a neo-Hookean material with a shear modulus of 0.5 MPa and a bulk modulus of 2000 MPa. This value of shear modulus is appropriate for a soft rubber. Boundary conditions were specified on the top and bottom surfaces of the rubber profile to simulate bonding to an effectively rigid mortar. The small strain vertical and out-of-plane horizontal stiffness were calculated. The final design is shown in Fig.2 and its properties are given in Table 2.

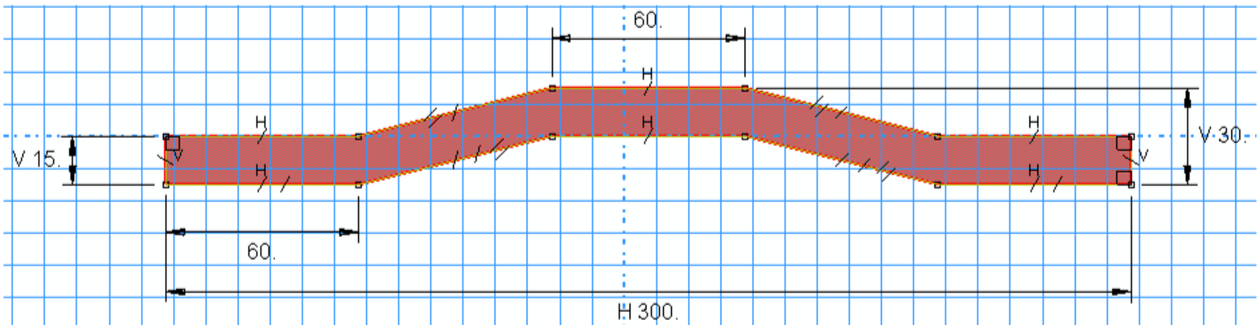

Fig. 2 – Joint profile. Dimensions in mm.

Table 2 – Stiffness characteristics of the rubber joint shown in Fig. 2

k_z (FEA) kN/mm/m	k_x (Eq. 2) kN/mm/m	k_y (FEA) kN/mm/m
3826	10	32

The calculated horizontal in-plane stiffness does not quite meet the design requirement. To reduce it would require either an increase in the profile thickness or a reduction in its width. The former option was not practical due to space constraints and the latter would have the undesirable consequence of reducing the vertical stiffness below the requirement, unless a laminated design was adopted which would be much more expensive to produce.

The total height of the profile was 30 mm. This meant that it would not be possible to accommodate a layer of grout across the whole area of the joint. Instead, the grout would fill the spaces around the profiled rubber shape.

3.2 Out-of-plane behaviour

It is important that the wall with the embedded rubber joints is able to resist the out-of-plane force without collapse. FEA of various designs of embedded rubber joint was carried out to determine which profile would be best able to do this. The results for the chosen profile, and two other profiles with similar stiffness characteristics, are presented here. The model consisted of four layers of masonry, modelled as a linear elastic material with a Young's modulus of 4.5 GPa, and a Poisson's ratio of 0.15 interleaved with three layers of rubber, modelled as a neo-Hookean material with a shear modulus of 0.5 MPa and a bulk modulus of 2000 MPa. The total height of the wall was 2650 mm and its thickness was 300 mm. A cross-section of the wall was modelled in plane strain.

Frictional contact was modelled between the rubber and the masonry. Pressure dependent friction was modelled according to Thirion's relationship [7]:

$$\frac{1}{\mu} = a + \frac{bP}{E} \tag{3}$$

where μ is the coefficient of friction, P is the normal pressure, E is Young's modulus of the rubber and a and b are constants. Values of 0.57 and 0.36 MPa^{-1} were used for a and b/E respectively, taken from data for rubber against ground steel in [8].

A side force was applied to part of the two middle layers of masonry as shown in Fig. 3. The required magnitude, determined by the University of Padua, was 195 $kN.m^{-1}$ over two 200 mm high portions of masonry. This was converted to a uniform pressure of 0.4875 MPa. The side load was resisted by pinning two corners of the model with a fixed-displacement, but free-rotation, boundary condition.

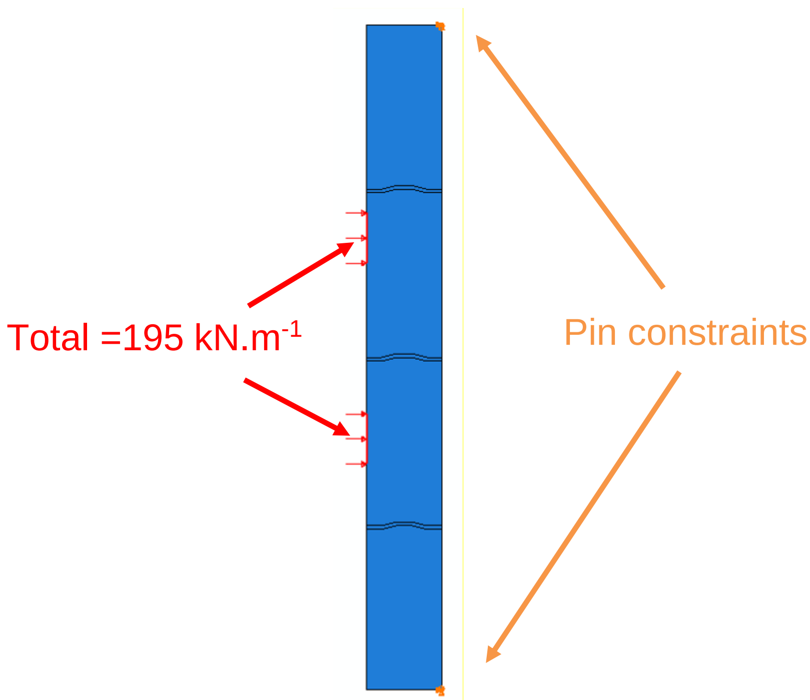

Fig. 3 – FEA model for simulating out-of-plane horizontal loading of the wall

Owing to convergence difficulties with Abaqus Standard, Abaqus Explicit v6.10 was used to run the analyses. A nominal density of 1000 $kg.m^{-3}$ was used for both the masonry and the rubber and the side load was applied as a smooth step amplitude over a step time of 0.1 s so that a quasi-static solution was obtained.

The maximum principal stress distribution is shown for three profiles under the maximum design side-load in Fig. 4. Friction and keying between the rubber and the masonry is required to prevent excessive relative motion of adjacent layers of bricks such that they pop out. All of the profiles shown in Fig. 4 were able to support the maximum side-load but, due to its smooth curved profile, Design (c) allowed rotation of the masonry layers and thus provided less resistance to collapse of the wall. A keying mechanism prevented such rotation for Designs (d) and (e) but the sharp corners in Design (d) resulted in some stress concentrations in the masonry. The simulation results also indicate a significant stress concentration at the top and bottom corners of the wall where the pin constraints were imposed, but these are an artefact of over-constraint of the pin constraints; in reality, compliance of the rubber joints would allow some movement of the masonry so that this stress concentration would be relieved. Elsewhere, the maximum tensile stress in the bricks was modest (around 0.5 MPa) so damage to the masonry would not be expected due to the out-of-plane motion.

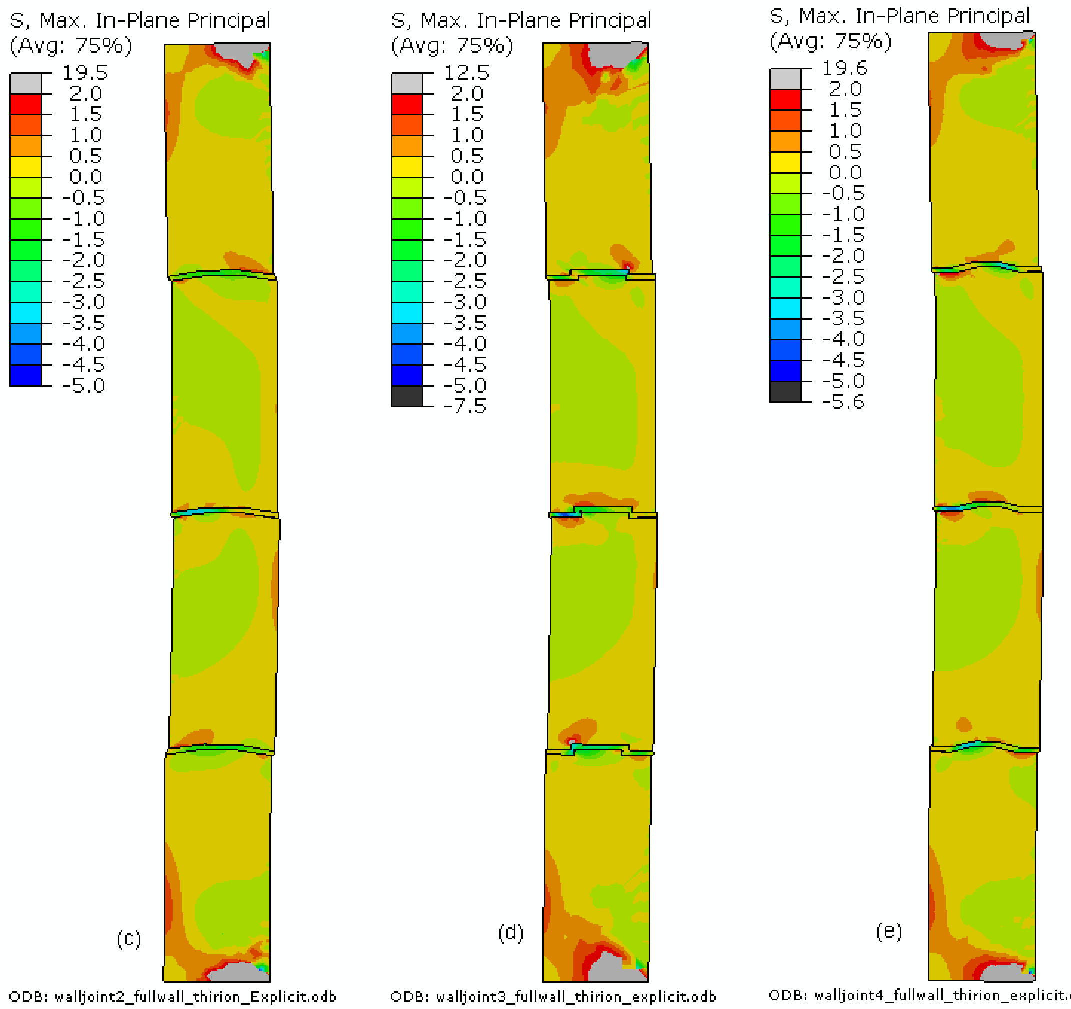

Fig. 5 – Maximum principal stress distribution in the wall under a 195 kN.m^{-1} side load with different profiles of rubber joint. Contours show maximum principal in-plane stress in MPa.

4. Manufacture of the joints

Based on the calculations and FEA reported in the previous section, sufficient confidence in Design (e) of Fig. 5 was gained to submit it for laboratory testing within a masonry wall in a RC frame at the University of Padua.

The joints were manufactured at TARRC by compression moulding 500 mm long sections, shown in Fig. 6. The sections were laid end-to-end to form a complete horizontal joint.

Fig. 6 – TARRC's horizontal joints used in the laboratory structural tests at the University of Padua

5. Review of experimental performance of the rubber wall-joint within an RC frame with masonry infill

Veralto et. al [9] tested the joints as part of the INSYSME project experimental campaign conducted at the University of Padua. Their test setup was similar to that shown in Fig. 1, with an R.C. frame (4150 mm span and 2570 mm height) filled with rows of masonry blocks in four strips separated by three layers of horizontal rubber joints. Two vertical layers of isotropic rubber pads were installed between the frame and the masonry wall. They conducted a series of in-plane and out-of-plane tests on the wall with and without the rubber joint. Prior to each test the columns of the frame were each subjected to a constant compressive load of 400 kN to account for the load due to the rest of the structure. For in-plane tests, three horizontal sinusoidal displacement cycles were applied to the upper beam. This test was repeated with increasing amplitude so that the drift between the top and bottom beam of the frame ranged from 0.05% to 2.4% in steps of 0.1%. For the out-of-plane tests the load was applied perpendicular to the plane of the wall for successively increasing peak loads up to 60 kN. A final test to establish the ultimate displacement capacity of the wall was carried out by applying an increasing out-of-plane load. Their results showed that:

- As expected, the confined masonry wall without the innovative joints exhibited very high initial in-plane stiffness. This stiffness decreased beyond 0.1% drift and the force reached a maximum at around 0.8% drift. This is due to progressive development of diagonal cracks which grow in number and size with increasing drift amplitude. Beyond 1.2% drift up to the maximum of 2.4% progressive crushing of the top and bottom corner blocks was observed. By the end of the in-plane tests both the infill masonry and the RC frame were damaged significantly. In contrast, the wall containing the rubber joints exhibited no drop in force with increasing drift and insignificant damage. It also reduced the maximum in-plane load carried by the infill by 56%.
- In the out-of-plane tests, the masonry wall without the rubber joints exhibited a high initial stiffness and a maximum force of 173 kN with an out-of-plane deflection of 27.9 mm in the middle of the wall. In contrast the wall containing the rubber joints reached a maximum out-of-plane force of 139 kN (25% reduction) and deflection of 33.6 mm. This is due to the lower vertical stiffness of the wall. Because the rubber joint reduces in-plane damage, walls with a rubber joint exhibited a higher initial stiffness than plain walls in out-of-plane tests conducted after completion of the in-plane tests.

6. Summary and Conclusions

Several different rubber profiles were investigated for their suitability to provide a compliant joint in infill walls. The dimensions were adjusted to meet stiffness requirements provided by University of Padua. It was not possible, with a simple design, to meet all the requirements, so a design with a slightly higher horizontal in-plane stiffness was accepted.

FEA of the wall indicated that it was capable of surviving an out-of-plane side load of 195 kNm^{-1} without collapsing. There is potential for undertaking more detailed modelling:

- to check the stress distribution against a quantitative failure criterion for masonry;
- to consider a more realistic loading regime, in which the side loads arise from the dynamic behaviour of the wall during an earthquake.
- to examine the in-plane behaviour in a seismic event.

The innovative rubber joints were manufactured. They were installed and tested within the rows of masonry blocks confined within reinforced concrete frames following an invitation by the coordinators of the INSYSME project funded under the 7th Framework Program of the European Commission. The results of these tests [9] suggest that the introduction of the rubber joint considerably reduces the masonry damage and provides excellent out-of-plane performance in terms of strength and initial stiffness.

Acknowledgements

The authors thank Alan Harris and the millroom staff at TARRC for designing the mould and fabricating the rubber joint in a very short time. The support of the University of Padua, in particular Prof. Francesca da Porto and Dr Giovanni Guidi, in the definition of the rubber joint stiffness requirements is very much acknowledged.

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