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EXPERIMENTAL AND NUMERICAL ANALYSIS OF FLEXIBLE POLYMER CONNECTIONS FOR CLT BUILDINGS

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ABSTRACT: This paper explores the possibility of using flexible adhesives to dissipate energy in CLT buildings during earthquakes. In the first series of tests, a rod glued in a CLT panel with flexible adhesive was investigated. The connection was tested in pull-pull configuration using cyclic, tension-only loading. Different rod diameters and different thicknesses of the glue layer were tested. The tests have shown that the adhesive can resist large deformations and exhibits fairly large energy dissipation capacity. Based on the test results the numerical analyses were performed to test the behaviour of the connection when applied in CLT buildings. Existing constitutive models available in OpenSees software were used to simulate the specific hysteretic behaviour of the connection. The results have shown that the CLT wall anchored with "flexible" glued-in rods would have a significant energy dissipation capacity if a sufficient number of them were used as the hold-down devices. Such system could be used to dissipate energy in seismic areas.

KEYWORDS: CLT connections, flexible adhesive, polyurethane, energy dissipation, equivalent viscous damping, cyclic tests, dynamic tests

1 MOTIVATION AND BACKGROUND

Cross-laminated timber (CLT) is becoming an increasingly popular building material in Europe and across the world. The versatility of CLT has encouraged engineers to build multi-storey structures in earthquake prone areas, although there is very little experience and research about the behaviour of such structures during earthquakes.

The behaviour of CLT buildings during earthquakes depends mainly on the behaviour of the connections between adjacent panels. If the connections between the panels are strong enough and resistant to cyclic loading these structures are able to achieve damage-free performance even during the strong earthquakes. However, if the connections are too rigid, large accelerations can occur in the upper stories. This may result in injuries to occupants and damage to property which is not acceptable in terms of serviceability. Therefore, the structural system should be modified to incorporate dissipative behaviour. This can be achieved with dissipative connections which may be installed in different parts of the structure. Several solutions of dissipative connections have already been suggested so far to improve the ductile response of CLT buildings. Some authors have suggested improving the conventional steel angles and hold-downs. Scotta et al. [1] developed a "butterfly" connector which can be used as vertical and horizontal connection (it performs well in tension and shear) while Latour et al. [2] developed an hourglass-shape hold-down device. The main idea of both solutions is to stimulate the dissipation of energy at the desired locations in steel joints rather than to allow brittle failure in wood. Some other researchers have been looking for solutions based on energy dissipation through friction. Loo et al. [3] proposed an energy dissipating slip-friction device with elasto-plastic behaviour. When the slip-force of the connector is achieved, the wall will uplift and rock, thus activating the sliding mechanism in the slip-friction connectors. Similar solution was suggested by Hashemi et al. [4] who introduced a slip-friction connection composed of springs. The connection has dissipative and self-centring characteristics. Yet another group of researchers has been investigating a so-called hybrid system. This system originates from precast concrete structures and combines the use of unbonded post-tensioned tendons with grouted longitudinal mild steel bars or energy dissipation devices. The hybrid system has already been successfully tested for Laminated Veneer Lumber (LVL) assemblies [5], which led to implementation of LVL

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hybrid rocking wall systems for high seismic performance timber buildings in New Zealand [6].
The experiments of the abovementioned connections mainly demonstrate enhanced dissipation characteristics and thus improved seismic response compared to traditional connections. However, there are some drawbacks associated with the mechanical connectors. In such systems, the dissipation is concentrated in a small area which must be very carefully designed in order to prevent damage to other parts of the structure. In addition, the mechanical connectors are robust and difficult to hide inside the construction.

Therefore, the aim of this research is to investigate alternative options for energy dissipation by employing adhesive joints between the panels made of deformable polymer materials. In the presented paper the basic concept is first described with possible applications in CLT structures. To check the concept some tests have already been performed on the connections with glued-in rods and some basic characteristics have been obtained. The first attempts were also made to model the response of the connections in order to verify the performance of the connections when applied in buildings.

2 CONCEPT

The main idea of the proposed solution is to dissipate seismic energy through the adhesive joints between timber elements. The concept has already been investigated by Cracow University of Technology (CUT) in combination with concrete and masonry structures. CUT, in cooperation with SIKA Company, developed a family of various flexible adhesives based on polyurethane. The adhesives were initially developed for elastic joining of structural elements and to provide protective coating. It has already been successfully used for the repair and strengthening of cracked masonry structures [7]. As demonstrated in cyclic tests, the material is capable of dissipating energy, which is clear from the area enclosed by the hysteretic loops [8,9]. The initial pull-off adhesion tests have already been done on timber elements. The tests show that the adhesive could also be used for this purpose.

The flexible adhesive with the energy dissipating properties allows for various applications in CLT structures to increase their seismic performance. Two suggestions are listed below.

1) Vertical joints between adjacent panels
Adhesive can be applied to the vertical joints between adjacent panels. For this purpose, the panels should be broken up into narrower wall segments as shown in Figure 1. The narrow wall segments allow panel rocking movement during the seismic load which induces shear deformations in vertical joints (the thickness of the adhesive should be large enough to accommodate large shear deformation). The hysteretic and viscous material damping, which takes place in the adhesive during the repeated cyclic loading, leads to dissipation of seismic energy. In order to allow unhindered rocking movement of the panels, other connections should be designed for this purpose. In particular, the mechanical connections between the panels and the walls should allow vertical movements of the walls. The vertical joint should have large surface of the adhesive joint to ensure the out-of-plane stability and insulation of the wall. This could be achieved by using standard forms of connections, such as simple lapped joint, tongue and groove, dovetail joint, etc.

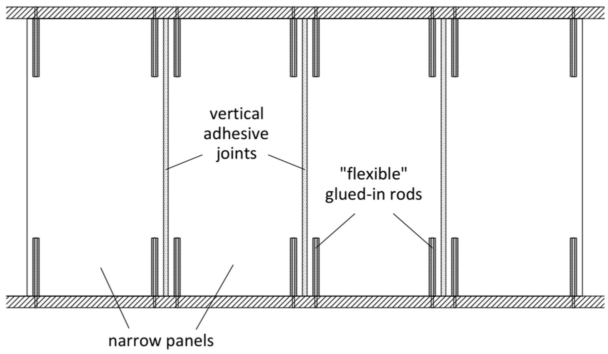

Figure 1: *Flexible adhesive joints in CLT structures – possible applications*

2) "Flexible" glued-in rods
"Flexible" glued-in rods can be used at the connection between the panel and the wall at the top and/or bottom of the wall (Figure 1). As in the case of vertical joints, the wall segments should be narrow enough to allow rocking. The rods are glued in the panel with a thick layer of flexible adhesive. During the seismic loading the panels rock which causes the bars to be pulled out of the panels. While pulling the rod the energy is dissipated through the shear deformation of the adhesive layer.
In general, "the flexible glued-in rods" could be used in any location where there are movements between elements during the seismic loading. Different materials and different profiles may be used for the rods. For better efficiency, the glued-in rods may be used in connection with the vertical joint described in the previous section.

The concepts listed above are theoretical. Experimental tests of the performance of glued-in rods are shown below.

3 EXPERIMENTS

In the first series of tests, a rod glued in a CLT panel with flexible adhesive was investigated. The experiments were performed on Zwick Z2500Y testing machine at the Slovenian National Building and Civil Engineering Institute (ZAG). The specimens were cut out of a 5-layer CLT (lamellas 33-20-34-20-33 mm). The dimension of specimens was 25 cm × 30 cm × 14 cm. A hole for inserting threaded rods was drilled on two sides. This enabled the implementation of the so-called "pull-pull" tests (Figure 2).
At the supported end, a large diameter rod (Φ20 mm) was inserted in the CLT 10 cm deep. The rod was glued to the CLT with an epoxy adhesive (HILTI RE 500). This ensured a large rigidity and large resistance of the

fixed support. At the tested end a threaded rod with smaller diameter (Φ12 mm and Φ16 mm) was glued in with an elastic polyurethane sealant (Den Braven Zwaluw Polyurethane-50 FC). The sealant has elastic properties similar to the SIKA adhesive [7-9] but it has lower pull-off and shear resistance. The sealant has the following properties: modulus at 100% strain is equal to 0.6 MPa, elongation at break is equal to 500%, and tensile strength is equal to 1 MPa.

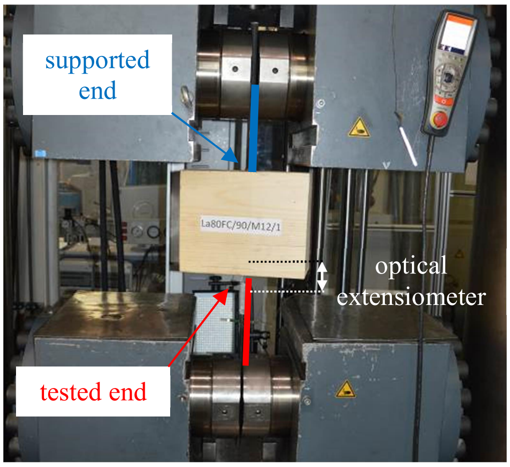

Figure 2: *Test set-up*

Two different rod diameters were used in order to test two different thicknesses of the glue layer (2 mm and 4 mm). In both cases the bonded-in length of the threaded rod was 80 mm. In some cases the rod was oriented perpendicular to the grain of the core lamination while in other cases the rod was oriented parallel to the grain of the core lamination. Two samples with the same characteristics were tested to verify the scattering of the results. The scheme of tests is shown in Table 1.

Table 1: *The scheme of tests*

Specimen	α [°]	Φ_a [mm]	$\Phi_{a,r}$ [mm]	t [mm]	n
La80FC/0/M12	0	20	12	4	2
La80FC/0/M16	0	20	16	2	2
La80FC/90/M12	90	20	12	4	2
La80FC/90/M16	90	20	16	2	2

α …rod orientation relative to the grain of the core
Φ_a …diameter of the hole at the tested side
$\Phi_{a,r}$ …diameter of the rod at the tested side
t …thickness of the glue
n …number of samples

The glued-in rods were tested under a cyclic loading in the tension direction only. The loading was applied to the samples using a displacement-controlled method. The induced displacements approximately followed the ISO 16670 [10] displacement protocol (Figure 3). The rate of loading was 1 mm/s. According to ISO protocol, the small-amplitude cycles with single repetition are followed by large-amplitude cycles with three repetitions until the failure occurs.

The displacement at failure was estimated at 64 mm. The relative displacement of the connection between the rod and the CLT panel was measured with an optical extensometer which is built into the Zwick test device. The displacement was measured near the tested surface at the distance of 5 cm (Figure 2). In addition, the behaviour of the connection at the tested end was recorded with a HD camera.

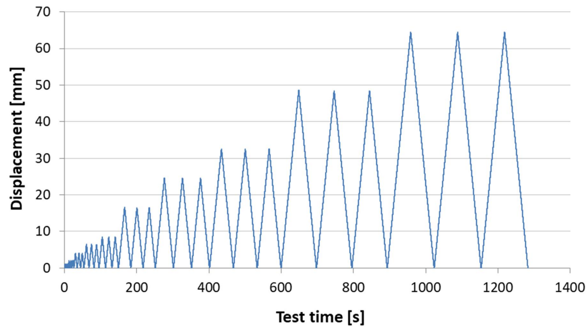

Figure 3: *Cyclic displacement schedule*

As expected, the behaviour of the connection during the cyclic loading was highly elastic. All deformations took place in an adhesive joint and the failure (rod pull-out; Figure 4) mainly occurred within the glue line (cohesive failure of the adhesive). The connection resisted large deformations and large energy dissipation was observed from start up to the ultimate displacement of 64 mm. The response of the connections in terms of actuator force versus relative displacement of the joint is presented in Figure 5. Hysteretic curves show a typical hyperbolic hardening up to maximum load capacity. This is followed by an exponential decrease of strength until the failure. In re-loading a characteristic pinching effect can be observed.

Figure 4: *Rod pull-out*

Some other conclusions can be made based on the hysteretic response:

1. Load-carrying capacity of the joint is approximately proportional to the thickness of the adhesive assuming all other properties are the same. With a smaller thickness of the adhesive, larger load can be transferred.
2. Load-carrying capacity of the joint with 90° rod orientation relative to the grain of the core is

approx. 15% higher compared to the joint with 0° rod orientation relative to the grain. This is due to the better adherence of the adhesive perpendicular to fibres.

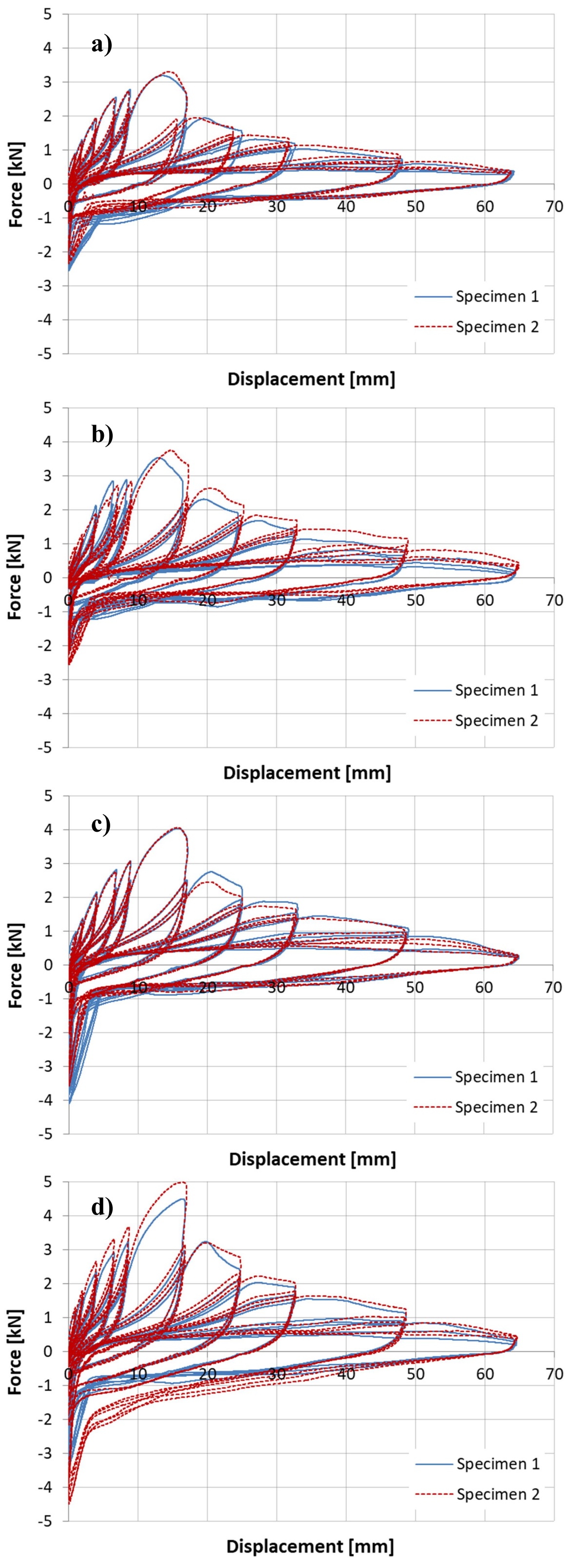

__Figure 5:__ Results of cyclic tests: a) M12; 0° rod orientation, b) M12; 90° rod orientation, c) M16; 0° rod orientation, d) M16; 90° rod orientation

In order to characterize the performance of the connections during the earthquake loading the amount of dissipated energy was evaluated in terms of equivalent viscous damping. The equivalent viscous damping (ξ) was evaluated from the hysteretic response as a ratio of the dissipated energy (E_d) to the potential energy (E_p) as suggested by Chopra [11]. The equivalent damping was calculated for each individual loading cycle. The values for the first and the last cycles are presented in Figure 6 (figure shows the values of equivalent viscous damping over several deformation steps until the failure). As shown in the figures, the values for moderate amplitudes (up to the maximum load) range between 0.05 and 0.1 and then increase even further with larger amplitudes.

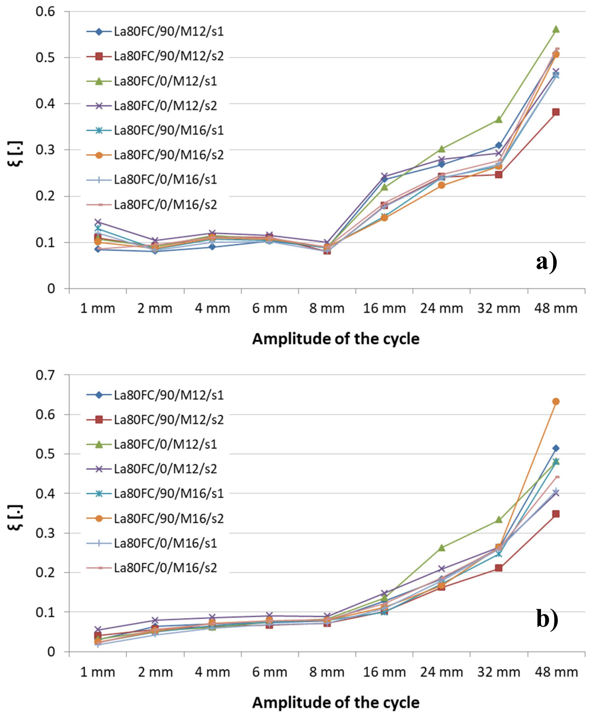

***Figure 6:** Equivalent viscous damping: a) 1st cycle, b) 3rd cycle*

4 NUMERICAL ANALYSIS

To test the behaviour of the glued-in connections when applied in CLT walls, a series of numerical analyses were performed in OpenSess [12].

First, experimental results of the connections were used to calibrate the equivalent single degree of freedom (SDOF) elements which represent the joints. The experimentally obtained cyclic response of the connections was modelled with a hysteretic material model proposed by Folz and Filiatrault [13]. The hysteretic model was basically developed to predict the response of wood shear walls and has been incorporated into the computer program SAWS [14] and OpenSees [12]. The model assumes hyperbolic force-displacement relationship until the ultimate load is reached. Beyond the ultimate load the load carrying capacity is reduced linearly until zero resistance. The cyclic response is additionally defined by six parameters which control the pinched, strength, and stiffness degrading hysteretic behaviour.

The SAWS model was used to predict the response in the tension direction of loading. To account for stiff elastic behaviour at small excursions in the negative direction of the loading, additional elastic-perfectly plastic material was constructed to act in parallel to the SAWS model. The elastic stiffness of the "compression material" as well as parameters describing the SAWS model were calibrated to match the experimental results. The following procedure has been applied for the calibration:

1. The envelopes of the load-displacement response were obtained for each cyclic test.
2. Part of the curve up to maximum resistance was approximated with the hyperbolic function according to SAWS model [13]. The regression analysis was performed using a least square method.
3. The post-capping response was approximately defined by assuming a linear relationship between the ultimate load displacement and the point corresponding to 80% drop of resistance.
4. Finally, the stiffness of the SDOF element in compression and the parameters that control the cyclic behaviour were determined iteratively by comparing the experimental and numerical cyclic response.

An example of a calibrated SDOF model is shown in Figure 7.

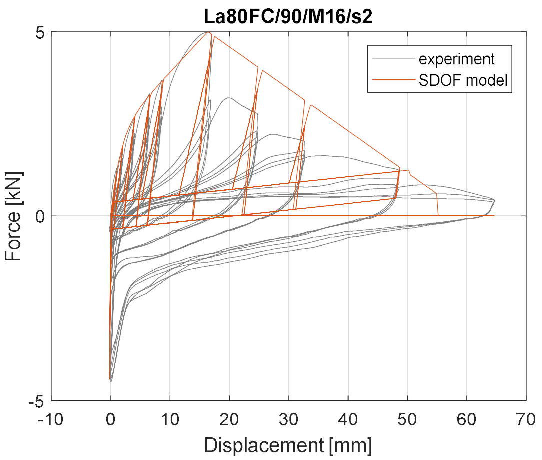

Figure 7: *Comparison of experimental and numerical results (SDOF model)*

Based on the calibrated SDOF model of connection, a simplified numerical model of a CLT wall was built. The planar model consisted of rigid frame elements (Figure 8) representing the CLT wall (the wall was assumed infinitely rigid) and two springs elements at the corners of the wall representing the glued-in connection. The springs allowed the movement in the vertical direction while the movement in the horizontal direction was restrained. The dimension of the wall was 2.5 × 2.5 m. The vertical loading at the top of the wall was assumed equal to 10 kN/m. A static cyclic loading was performed by controlling the horizontal displacement at the top of the wall. The induced displacements followed a loading protocol used in OptimberQuake cyclic tests of CLT walls [15]. The geometric nonlinearity was considered by means of P-delta effects.

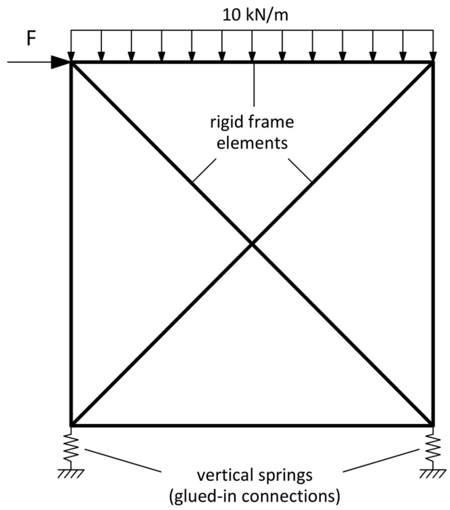

Figure 8: *Numerical model of CLT wall*

The initial numerical results have demonstrated that the resistance of the wall with two vertical springs with properties according to Figure 7 is too small to have a considerable effect on the seismic capacity of the wall (the resistance of the adhesive is negligible compared to the overturning resistance of wall). In order to provide a greater effect of adhesive joints, the strength of the connections should be increased. This can be achieved by increasing the number and/or diameter of the bars, by increasing the anchor lengths or by using a stronger adhesive. In order to verify this hypothesis, the load-carrying capacity of the vertical springs in the numerical model was assumed 10 times higher. In this case the results show a significant increase of energy dissipation capacity, which is clear from the area enclosed by the hysteretic loops (Figure 9). The energy dissipation capacity of the wall is comparable to the conventional CLT wall connected with the traditional mechanical connections [15]. This confirms our assumption that flexible adhesives (in particular "flexible" glued-in rods) can be used to dissipate energy in CLT buildings.

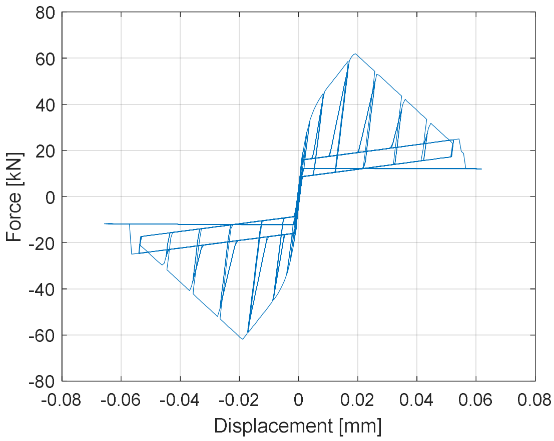

Figure 9: *Numerical response of a wall with "strong" connections*

5 CONCLUSIONS

The cyclic tension-only tests of rods glued in CLT with flexible adhesive were made. The tests have demonstrated promising behaviour of such connections when subjected to cyclic loading. The connection resisted large deformations and demonstrated fairly large energy dissipation capacity – the equivalent viscous damping ranged between 0.05 and 0.1 for moderate amplitudes and increased further with larger amplitudes. The tests have also shown that load-carrying resistance of the connection is proportional to the thickness of the adhesive and depends slightly on the orientation of the rod relative to the grain of the core lamination.

To test the seismic behaviour of the "flexible" glued-in rods when applied in CLT buildings, a series of numerical analyses were performed. First, the SDOF model of connection was calibrated based on the experimental results. The material model capable of simulating the pinched, strength, and stiffness degrading hysteretic behaviour (SAWS model) provided relatively good agreement with experimental results. In the next stage, the SDOF model of the connection was incorporated into the numerical model of the wall and a static cyclic analysis of the wall was performed. The results have shown that the resistance of the wall with two glued-in rods in the corner is too small to have a considerable effect on the seismic capacity of the wall. However, if the load-carrying capacity of the connection was 10 times higher (this could be achieved with a larger number of rods and/or larger rod diameters) the energy dissipation capacity was significantly improved. The results confirm that CLT wall system with "flexible" glued-in rods can be used to dissipate energy in seismic areas.

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