Earthquake Protection of Residential Buildings: New Resilient Systems for Light Timber Framing

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ABSTRACT

Residential houses are mostly constructed using light timber framing. The common seismic solutions available in the market for such low-rise buildings are based on yielding of sacrificial elements (such as nails or hold-down brackets) which will get damaged during an event. As a result, after a severe earthquake, repairs or replacement of parts will be needed which incurs costly post-event recovery as well as the vulnerability of the occupants given the risk of the aftershocks. In addition, due to the damage in the system, there would be loss of building stiffness and potentially a residual drift in the building. In this paper, new seismic solutions are presented specifically designed for the residential applications addressing the shortcomings of the current solutions.

The introduced systems incorporate an innovative damage-free cylindrical friction damper with full self-centring capacity implemented in tension-only steel strap cross braces as well as timber shear wall hold-downs. Such new systems could provide easily installed, cost-effective seismic solutions for residential buildings which have been less regarded compared to commercial structures though the earthquake impact could be even more crucial given directly affecting the residents and the families in the community. The paper presents the results of a full-scale testing of one of the proposed seismic resilient systems. Also, an equivalent ductility-based design approach is proposed, considering the specific hysteretic performance of these new systems. The findings demonstrate the efficiency of the proposed systems which could be also applicable for retrofitting of earthquake-prone residential buildings.

1 INTRODUCTION

During the last decades there has been a good advancement on the seismic design with a transition from "High-damage" to "Low-damage" concepts to address the need for quick functional recovery. However, the main question still remains whether the Low-damage concepts (mostly with replaceable fuses) are sufficient enough, in particular, for shaky regions where the aftershocks could be as high as the mainshock (eg, Kahramanmaras'

7.8M/7.5M earthquakes in Turkey-Syria, 2023 & Kaikoura's 7.8M/6.3M earthquakes in New Zealand, 2016). In such earthquake prone regions, there would be a high risk for the buildings significant damage during the aftershocks given the small chance for any repair or remedial work.

This paper presents new seismic "Damage-avoidance" concepts for the residential building applications with no post-event maintenance. It should be noted that these new systems could still provide easily installed and cost-effective seismic solutions for residential buildings which have been less regarded compared to commercial structures though the earthquake impact could be even more crucial given directly affecting the residents and the families in the community.

Fig. 1: Samples of seismic damage to residential buildings constructed by light timber framing

2 BACKGROUND

The current seismic solutions available in the market for residential low-rise buildings are mostly based on yielding of sacrificial elements (such as nails or hold-down brackets) which will get damaged during a severe event though providing a reasonable ductility to dissipate the earthquake energy. Some examples are presented in Figs. 2a to 2d for different possible lateral load resisting systems of truss bracing, tension-only straps and shear walls. As the most conventional system, use of plasterboard walls with specific nailing and anchorage of the back frame has been used widely (such as Gib bracing system). The hysteresis performance of the current seismic lateral load resisting systems typically includes a pinching behaviour showing strength and stiffness degradation through cyclic loading (such as the one shown in Fig. 3).

As a result, after a severe earthquake, repairs or replacement of parts would be needed which incurs costly post-event recovery as well as the vulnerability of the occupants given the risk of the aftershocks. In addition, due to the damage in the system, there would be loss of building stiffness and potentially a residual drift in the building. In this paper, new seismic solutions are presented specifically designed for the residential applications addressing the shortcomings of the current solutions.

The research team has already been successful is introducing new damage-avoidance solutions for seismic protection of commercial and industrial structures (Bagheri et al., 2020; Hashemi et al., 2020; Veismoradi et al., 2021; Yousef-beik et al., 2021; Zarnani and Quenneville, 2015) being adopted in several buildings in NZ and overseas such as Nelson Airport new Terminal, Hutt Valley new medical Hub in Wellington and Fast & Epp HQ Office in Vancouver, Canada.

Fig. 2: Samples of seismic solutions for Residential applications: a) Truss bracing by Gamma brace Ltd., b) Tension-only straps, c) Steel shearwalls by Mitek Ltd., and d) Timber shearwalls by Simpson Strong-Tie Ltd.

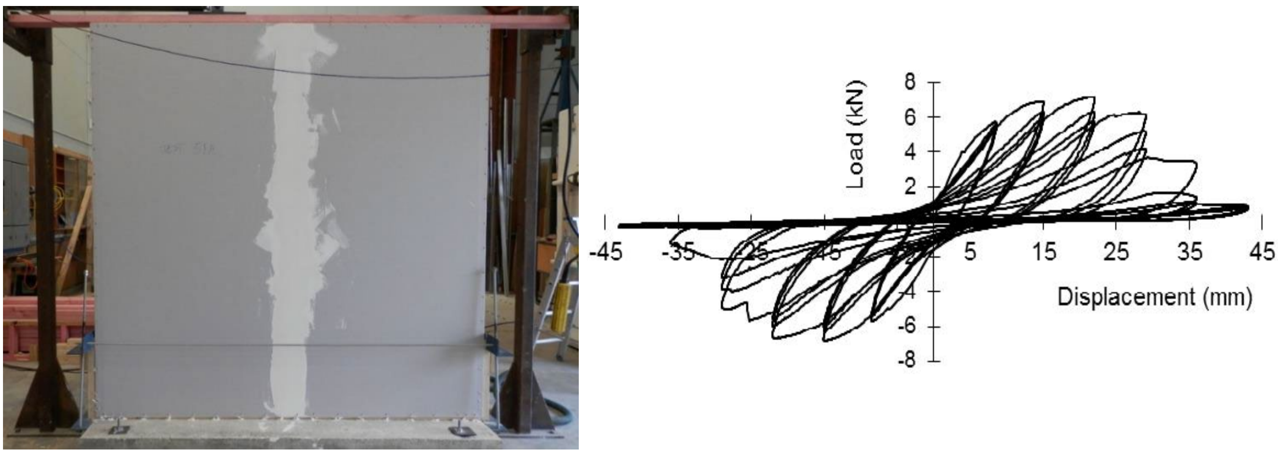

Fig. 3: Typical pinching performance of conventional lateral load resisting systems of residential timber framed buildings such as plasterboard walls (Liu and Carradine, 2019)

3 NEW RESILIENT SYSTEMS PROPOSED

The introduced systems incorporate an innovative Resilient Slip Friction Damper (RSFD) to be implemented in tension-only steel strap cross braces as well as timber shear walls. The RSFD is a friction-based damper that has a self-centring feature to restore it back after the full expansion phase. Fig. 4 shows the components of the proposed device. The internal shaft is clamped by the outer cylinder through using series of bolts providing the required friction. The slip force in the damper is set by the prestressing force in the clamping bolts as well as the disc spring stack. The self-centring feature of this connection relies on the disc springs, which are pre-stressed to overcome the resisting friction in reverse cycles, providing a resilient system. This damper has been invented and studied by Darani et al. (2017, 2018 and 2022) providing a flag-shaped hysteresis response. This new damper could address the shortcomings of conventional solutions with no post-event maintenance to withstand the aftershocks.

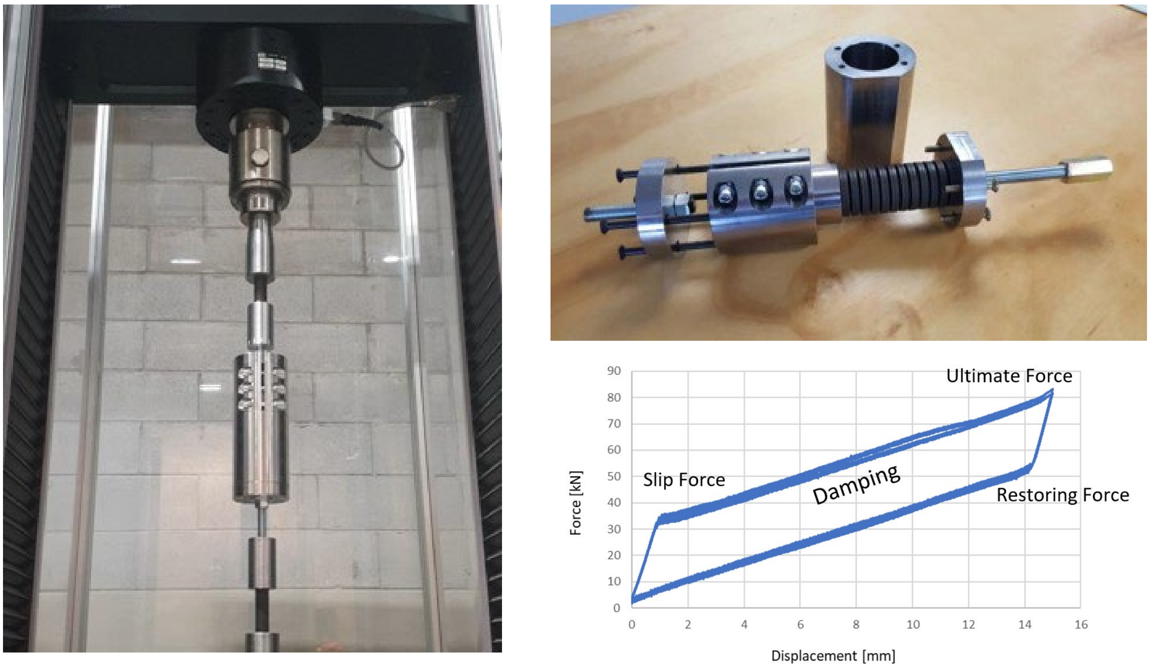

Fig. 4: The Resilient Slip Friction Damper (RSFD) and its flag-shape hysteresis performance

3.1 Resilient X-Brace

The conventional tension-only cross-braces using steel straps have been one of the common simple solutions to be adopted for resisting the seismic and wind lateral loads in residential buildings. However, given the appearance of slack and loss of stiffness in the system as soon as the initiation of the plastic deformation in the straps, they are not considered as a ductile system.

The proposed Resilient X-Brace is incorporating the RSFD's at the end of the diagonal double steel straps to provide damping and self-centring in a tension-only mechanism without any plastic deformation in the straps. This new system is specially designed for the residential applications offering a unique seismic technology, addressing the shortcomings of the current solutions. The arrangement of the components and the end gusset attachments are illustrated in Fig. 5.

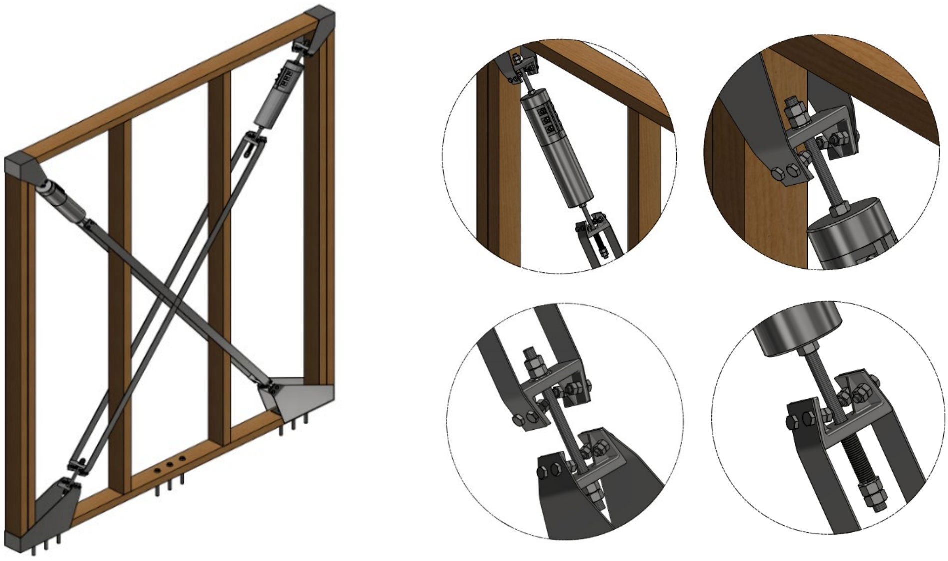

Fig. 5: The proposed Resilient X-Brace and its components

The proposed system has the advantage of providing high Bracing Units (within the maximum NZS3604 code limit of 150BU per meter length of the bracing) depending on the span length covering 2 to 4 bays (each spanning 600mm).

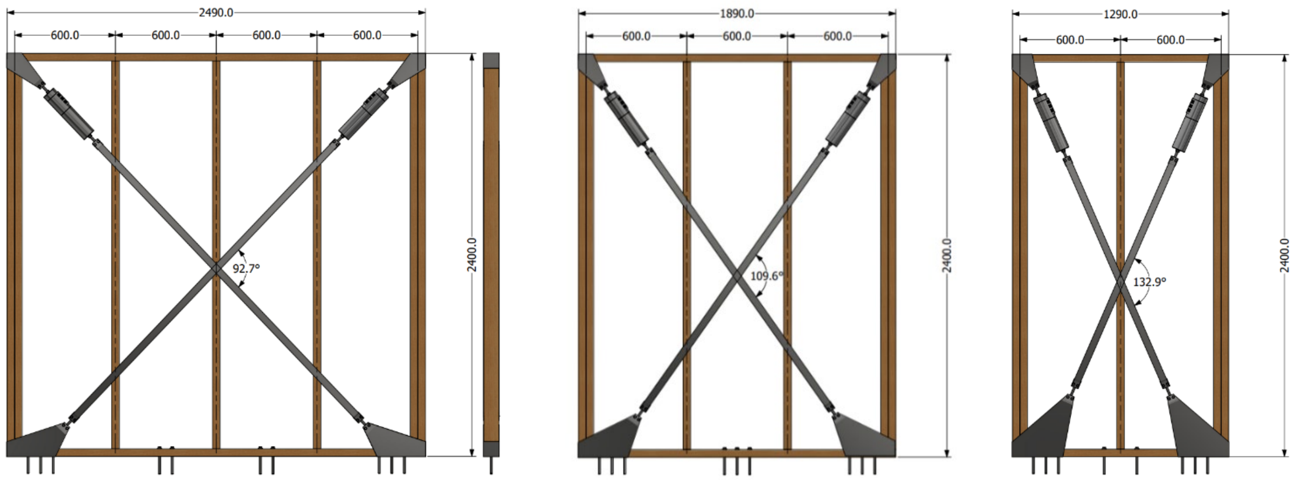

Fig. 6: The Resilient X-Braces covering different 2-, 3-, and 4-bay spans

3.2 Resilient Timber-Wall

As shown is Fig. 2, use of shearwall concept for residential light timber framing has already been introduced and adopted in the market such as by Simpson Strong-Tie and Mitek Ltd. The introduced ductility in such systems is based on the yielding of the wall hold-downs through plastic deformation occurring either in the anchor rods or nail connections. In the proposed Resilient Timber-Wall, the hold-down force is transferred to the RSFDs located at the wall corners to provide damping and a rocking mechanism for the wall as soon as the dampers get activated. The slip force at the activation of the damper is set to be beyond the serviceability limit state design load level (SLS). The lateral capacity of the proposed wall increases by its width (to provide more efficiency for the higher number of stories). The connections arrangement for different single- and multi-storey applications are shown in Fig. 7. It should be noted that this Resilient Timber-Wall is expected to provide a higher ductility and damping compared to the proposed X-brace concept given the higher initial stiffness of the solid wall compared to steel straps.

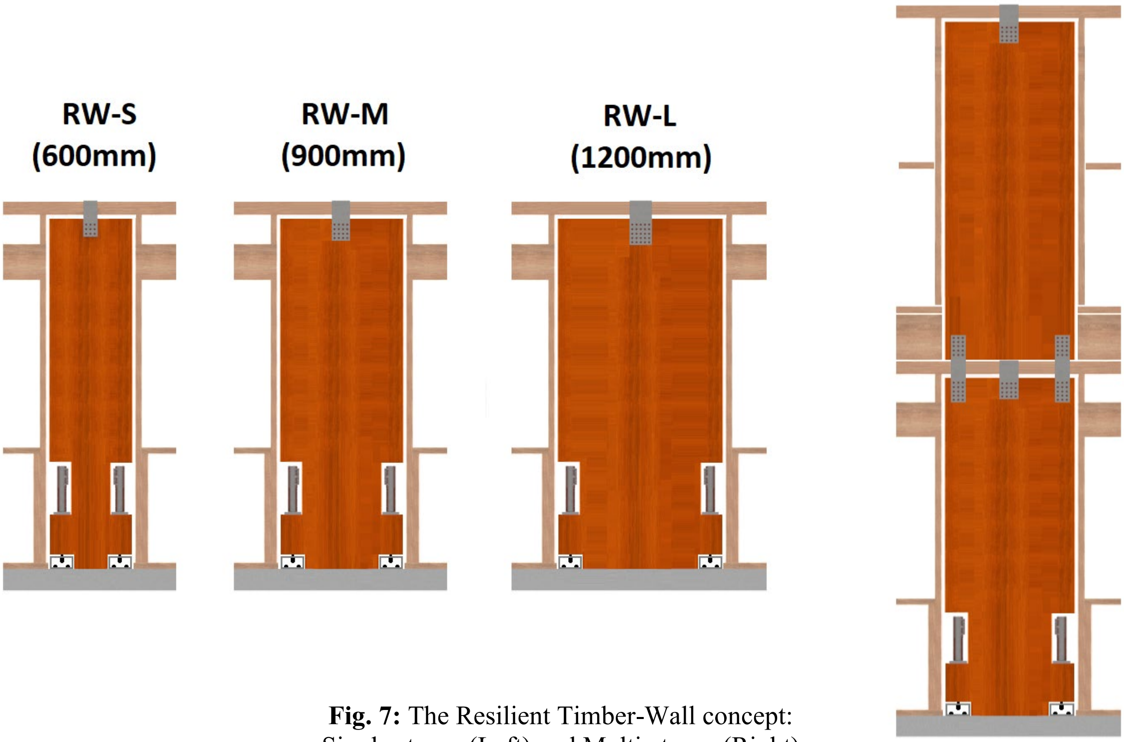

Fig. 7: The Resilient Timber-Wall concept:
Single storey (Left) and Multi-storey (Right)

4 EXPERIMENTAL VERIFICATION

As part of the testing program, the full-scale verification of the proposed Resilient X-Bracing system has been prioritised. As shown in Fig. 8, the test setup has been laid out horizontally (parallel to the concrete floor). Two steel brackets at the corners and one at the middle have been installed to transfer the reaction forces (tension/compression and shear) to the floor. The lateral loading has been applied using a hydraulic jack (equipped with load cell) at each side of the system, pulling a set of rods connected to the top timber plate of the braced frame.

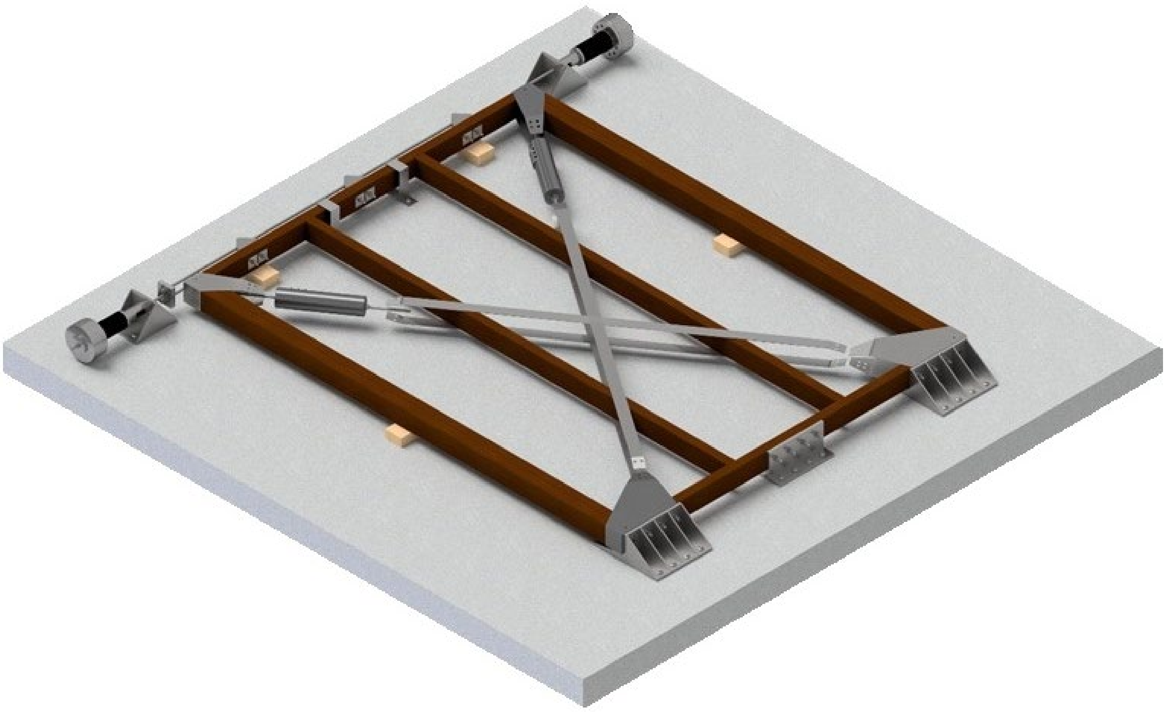

Fig. 8: The test setup for the proposed Resilient Timber-Wall concept

To minimise the damage to the plasterboards, the maximum drift considered in the building was limited to 1.5%. In addition, the plasterboards have been installed vertically at a maximum width of 1.2m with no nailing to the top and bottom plates and the middle noggings.

Fig. 9: The specimen tested (with & without the plasterboards)

The full self-centring performance of the tested system is presented in Fig. 10. As it can be deduced, the hysteresis curves are quite compatible demonstrating the repeatability of the performance after severe events without stiffness and strength degradation. The slip force is this test has been set at about 80% of the ultimate force. As shown in the curve, by adding more disc springs to the RSFD hold-downs, higher ductility could be achieved though requires a higher drift to be imposed to the building which would not be desirable given the possible damage to the plasterboards. It should be noted that no contribution has been observed from the plasterboard given the size and the nailing detail described.

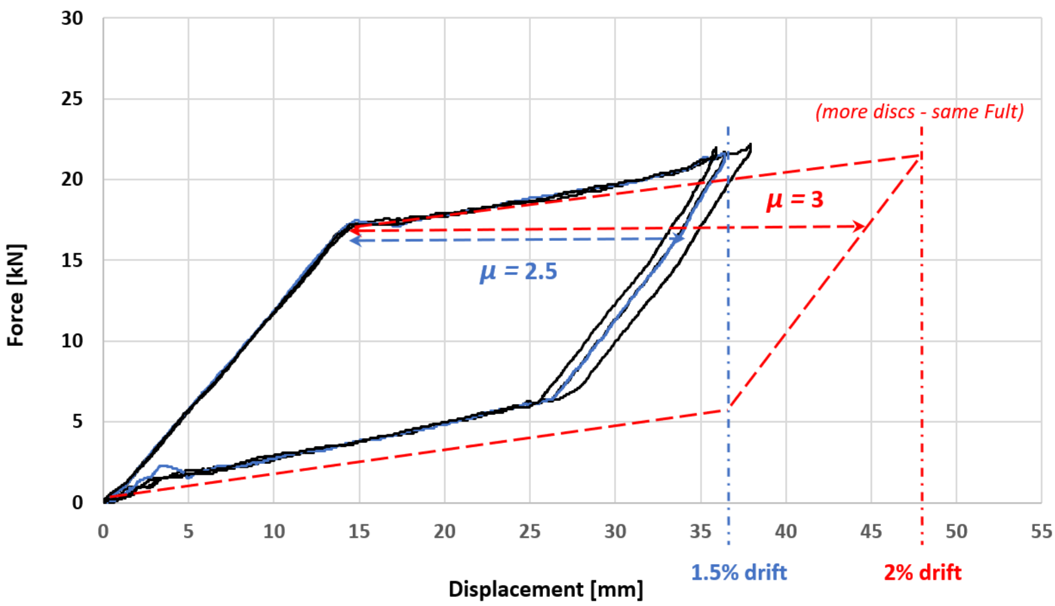

Fig. 10: The system flag-shape hysteretic response

5 PROPOSED DUCTILITY-BASED DESIGN APPROACH

As shown in Fig. 11, the Equivalent Energy Elastic-Plastic (EEEP) approach has been adopted as per ASTM E2126 to consider an ideal elastic-plastic response (red dashed line) to propose an equivalent ductility factor (μ_{eq}). As per ASCE7, by equating the Areas #1 & 2 under the linear and the elastic-plastic responses, the formula for calculating the ductility reduction factor (R_μ) can be derived as $R_\mu = \sqrt{2\mu_{eq} - 1}$. Also, as it can be found in the system performance curve (Fig. 12), there will be 20% difference between the slip force (as the design load, V_{des}) and the ultimate force (V_{ult}) due to the spring action in the damper to provide a full self-centring behaviour. It should be noted, extra 50% deflection capacity has been considered in the system (with no yielding) for the events beyond the ultimate limit state (ULS) to dissipate the extra input energy. As such, the overstrength factor (R_Ω) of the system can be determined as 1.3, the difference between the slip force and the maximum force, V_{max} (corresponding to 1.5 times the ULS deflection). To further verify the proposed ductility-based design approach, the NLTHA will be conducted as the next step of this study.

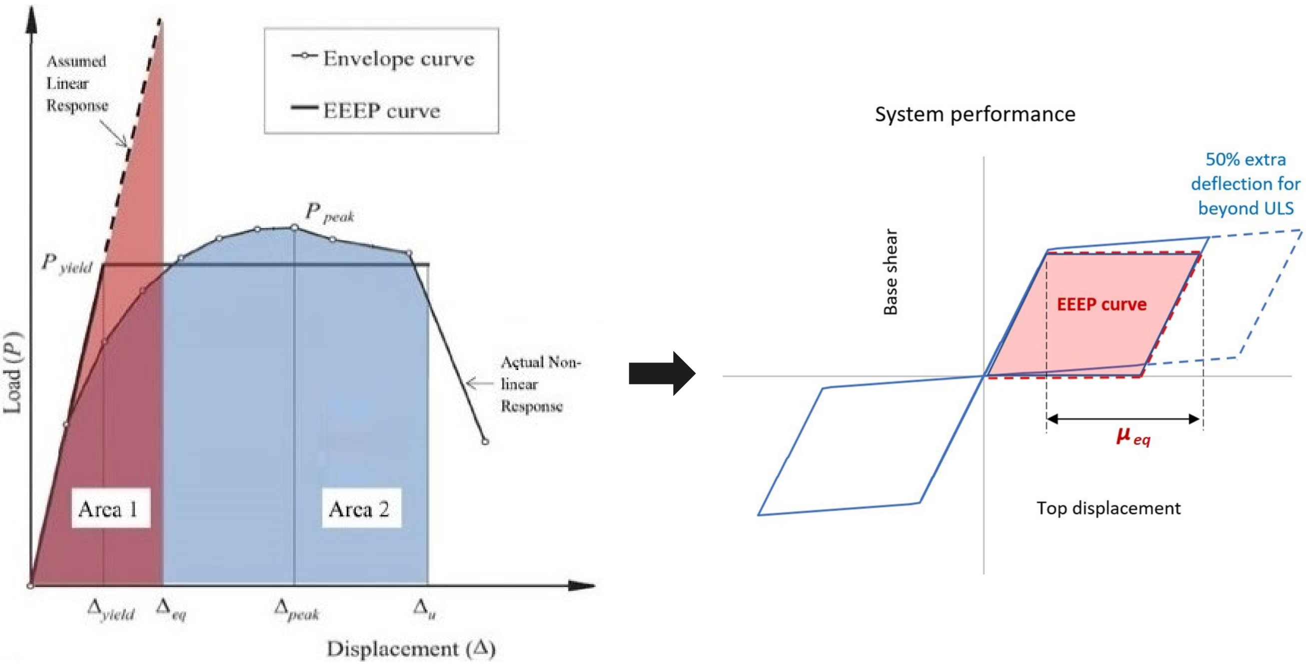

Fig. 11: Equivalent Energy Elastic-Plastic (EEEP) method for representing an equivalent elasto-plastic response (ASTM E2126, 2007)

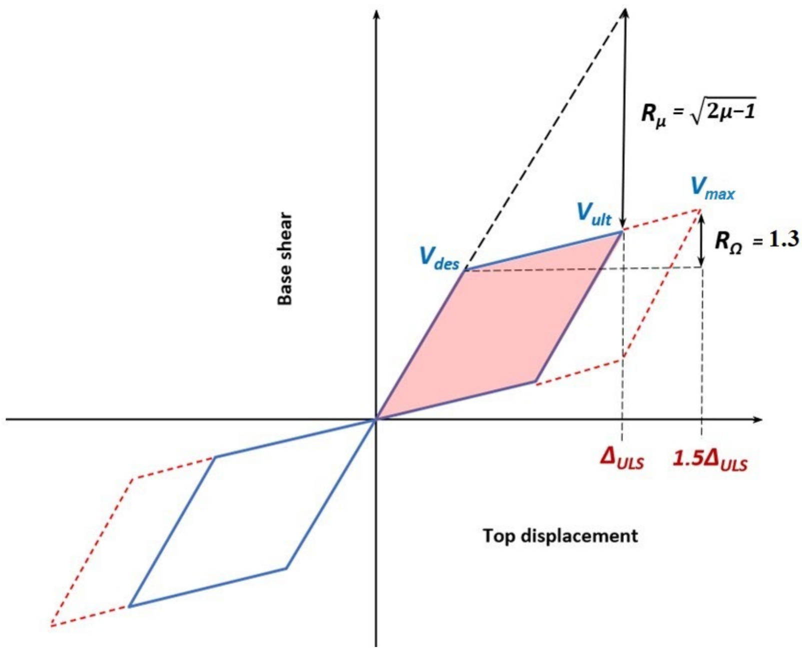

Fig. 12: Proposed ductility reduction factor (R_μ) and overstrength factor (R_Ω), following the ASCE7 guidelines

6 CONCLUSIONS

This paper presents new seismic "Damage-avoidance" concepts for the residential building applications with no post-event maintenance. It should be noted that these new systems could still provide easily installed and cost-effective seismic solutions for residential buildings which have been less regarded compared to commercial structures though the earthquake impact could be even more crucial given directly affecting the residents and the families in the community. The introduced systems incorporate an innovative damage-free cylindrical friction damper with full self-centring capacity implemented in tension-only steel strap cross braces as well as timber shear wall hold-downs. The test results verify the expected performance of the proposed systems without any stiffness or strength degradation during cyclic loading. Also, an equivalent ductility-based design approach is proposed, considering the specific hysteretic performance of these new systems. The findings demonstrate the efficiency of the proposed systems which could be applicable for both new builds as well as retrofitting of earthquake-prone residential buildings.

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