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Seismic resilience timber connection - adoption of shape memory alloy tubes as dowels

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Abstract

This study investigates a novel timber dowel-type connection system using superelastic shape memory alloy (SMA) bar and tubes as dowels, in order to provide self-centering effect. Double-shear connections with SMA and mild steel dowels were tested under dynamic loadings at different displacement levels. The results showed that SMA dowel-type connections have good self-centering behaviours and can mitigate the residual deformation effectively compared with steel dowel-type connections after excessive deformation, although the steel dowel-type connections present higher strength. These tests reveal that the connection with tube dowels show higher equivalent viscous damping ratio than those use solid bar as tube would allow larger deformation to dissipate energy. To demonstrate application of the benefit of this system, an analytical model of a 3-storey timber framed structure was built for parametric study. The results showed that the structures with conventional dowel-type type connections exhibit large unrecoverable deformation after timber framed structures experience an earthquake. In comparison, those with the connections developed in this project show limited unrecoverable deformation due to the self-centering capacity of the connections.

Keywords

timber dowel-type connection; shape memory alloy; tubes; self-centering effect

1. Introduction

In timber structures, connection is an important component because the connection is the weakest link of a structure. The stiffness of the connections significantly affects the structural deformation behaviours [1]. Concerning the conditions under cyclic loading, damping capacity of connections plays an important role in energy dissipation. Dowel-type connection is the most common type of timber connection, mainly relying on the bending capacity of the dowel and the embedment of the timber [2].

Nevertheless, timber connections are always the weakest in the whole structure under an extreme event such as an earthquake. As indicated by Casciati [3], the too weak timber connection could result in the performance below expectations and too resistant timber connection may not be able to dissipate energy. Casciati's study has investigated a timber connection which can dissipate energy but does not degrade the performance [3].

Steel is normally used in dowel-type connections, because steel contributes satisfactory stiffness and strength and has the benefit of low cost. However, as presented in our pilot studies [4], steel dowels in timber connections have large residual deformations, and residual deformations from connections can cause structural instability and collapse, so it is important to develop a self-centering connection system. Therefore, we used a dowel-type connection using superelastic shape memory alloy (SMA) dowel in our pilot research [4] and preliminary static compressive tests showed it was capable of being self-centering.

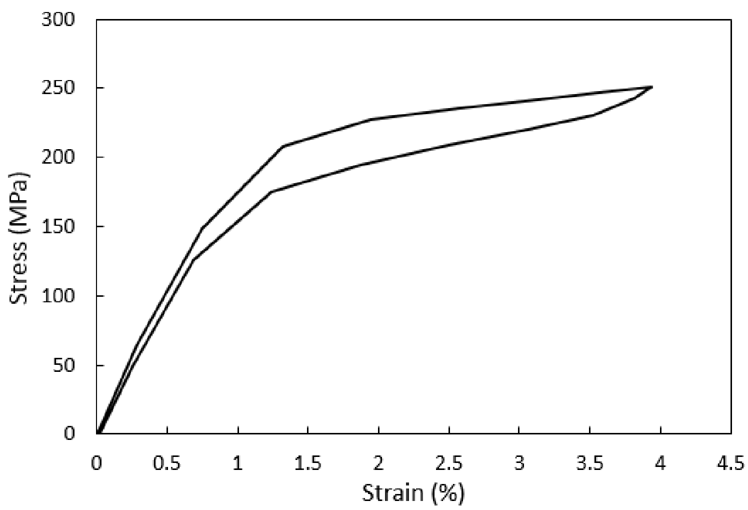


Figure 1 Stress-strain curve of Cu-An-Mn SMA bar tensile test

Superelasticity is one of the most important characteristics of SMA [5]. Figure 1 presents the result from one of our previous tensile tests on Cu-Al-Mn (Cu = 81.84%, Al = 7.43% and Mn = 10.73% by weight) SMA bars, and shows the superelastic behaviour which is able to recover the alloy to the original shape after a large plastic deformation. The application of SMA to civil engineering has been explored in previous research and the mechanical characteristics of SMA have been studied in relation to its performances in structures [6-11]. The fatigue properties of copper-based SMA have been studied regarding to its structural applications, and the dependency on temperature and strain range is highlighted [12-14]. SMA has been studied in steel connections for reinforcement, and research results show SMA is able to recover residual deformations and exhibit satisfactory energy dissipation capacities [15-19]. With regard to the particular self-centering effect of SMA on timber connections and the interest in whether SMA can benefit dowel-type timber connections, only our pilot research [4] has been carried out and more explorations are needed.

Associated with the enhancement of damping capacity for timber connections, Leijten [20] forwarded a concept that the solid dowel can be replaced by tube. Tube is easier to bend than a solid bar, thus the larger bending deformation can contribute more damping capacity [21]. Moreover, tube can be expanded by hydraulic jack in order to achieve suitable clearance with timber and in this way the stiffness of connection can be increased. However, the residual deformation of tubes caused by larger bending is an issue. The application of SMA tubes to timber connections would be practicable in addressing this problem.

In this study, a novel timber dowel-type connection with SMA is developed in which SMA solid bars and tubes are used as dowels to present self-recoverable function. Dynamic cyclic loadings with different amplitudes were carried out. Mild steel was employed in the same tests for comparison. This study presents how this novel dowel-type connection behaved in terms of self-centering capacity, damping ratio, strength and ductility.

More resilience may lead to less energy dissipation because the unloading curve retrieves to the origin and the hysteresis loop becomes small, and this can be seen in the tests on SMA-reinforced beam-column joints [22]. To find the balance between energy dissipation and resilience in timber connections, a parametric study was carried out by analysing the effect of connections on seismic performance of a timber structure so as to provide a basic understanding.

2. Materials and methods

The dowel-type connection used in this study is a double-shear connection with three pieces of timber and one dowel. A total of 30 connections were tested in this project. The timber used in the fabrication is sawn softwood graded C24, and the species is spruce (picea abies). The embedment strength, moisture content and density were tested in the laboratory. The tests for embedment strength strictly followed the BS EN383 [23], and the characteristic embedment strength paralleled to grain was 18.95 MPa from 10 samples. The average moisture content and characteristic density were 11.3% and 306.78 kg/m^3, respectively.

The fastener connecting the timber used both SMA and steel tubes and bars with outer diameter of 12 mm. Cu-Al-Mn (Cu = 81.84%, Al = 7.43% and Mn = 10.73% by weight) SMA was employed in this study, and was provided by Furukawa Techno Material Co. Ltd., Japan. The austenitic phase transformation end temperature (A_f) tested by the differential scanning calorimetry (DSC) method was -53℃, which means this Cu-Al-Mn SMA is superelastic at ambient temperature and has the aforementioned re-centering capacity. From material characterisation of Cu-Al-Mn SMA bars of 12 mm in diameter, the phase transformation stress was 200 MPa. The transformation stress of SMA has the dependence on temperature, e.g. the transformation stress increases with the rising temperature [24, 25]. The material for steel dowel was mild steel graded EN3B (080A15) [26], and its yield stress was 310 MPa. To present the effect of tube-shape dowels on the dynamic behaviours of the connection, despite using solid rods, SMA and mild steel tubes with 6 mm and 8 mm inner diameter holes and 12 mm outer diameter were applied to the tests.

The dimensions of experimental connections and test setup can be seen in Figure 2. As listed in the test protocol (Table 1), comparison tests in terms of different dimensions and materials of dowels were carried out. For each test, the loading protocol can be seen in Figure 3; connection samples were tested by displacement control at displacement amplitudes of 2, 4, 6, 8, 10 and 12 mm at a loading frequency of 1 Hz. As the damping stabilisation issue of SMA has been discussed [27], the damping decaying of SMA dowel-type connections at invariant displacement is studied in this paper. Therefore, there are 10 cycles in each loading displacement level as shown in Figure 3. Each testing condition was repeated using 5 samples.

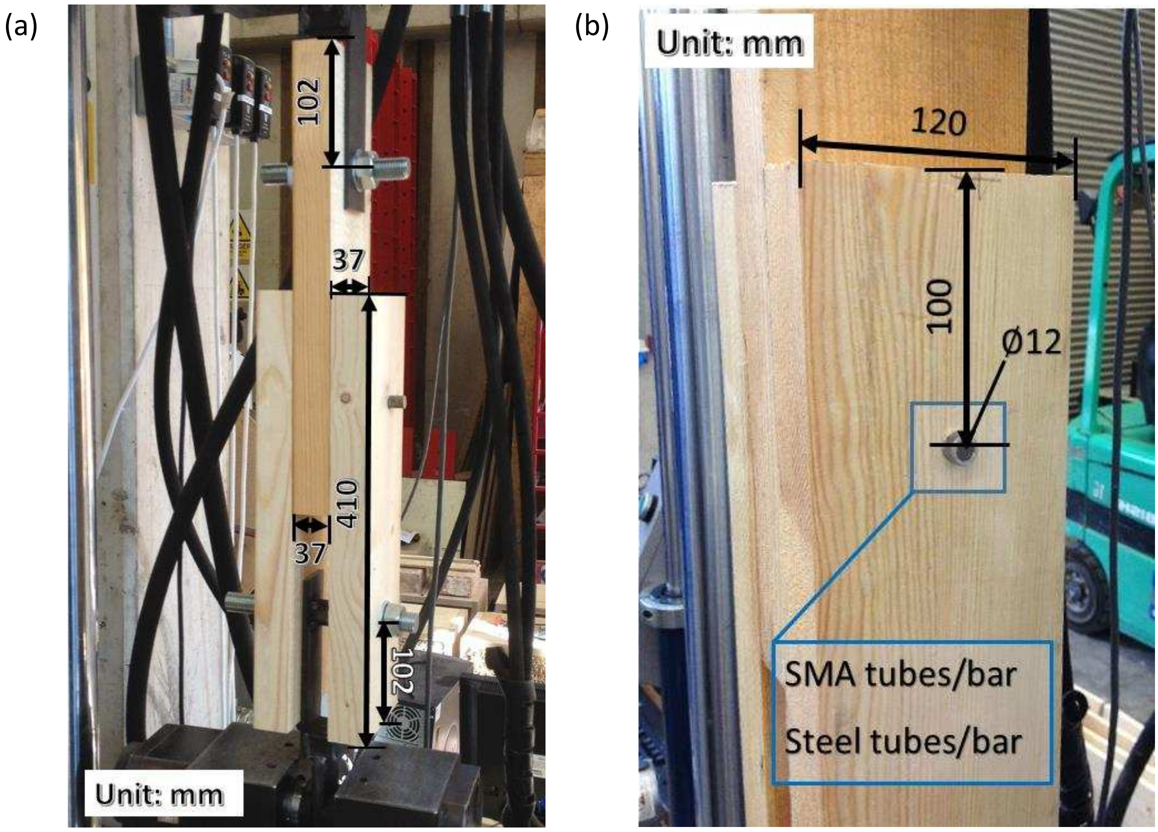


Figure 2 (a) Test setup of double-shear dowel-type timber connection; (b) Application of tube-type dowel to timber connection

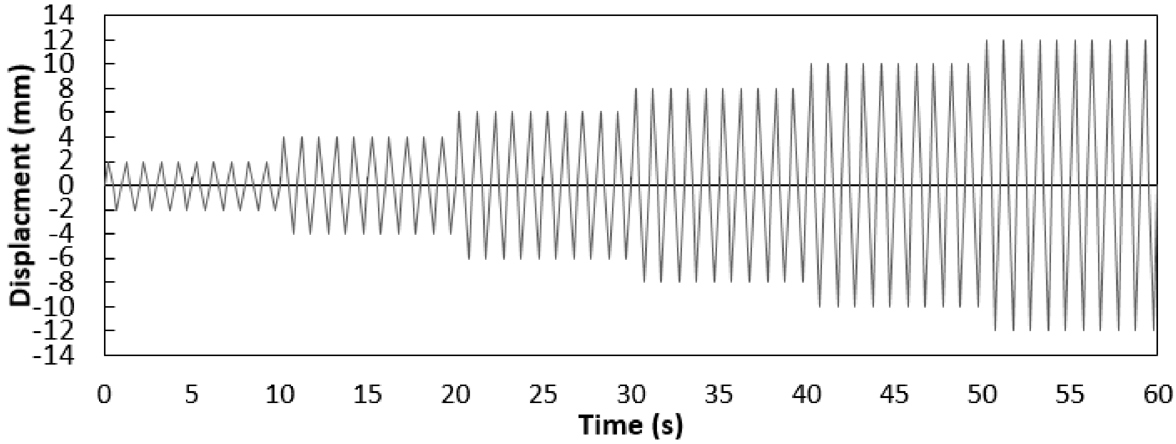


Figure 3 Loading protocol

3. Results and discussion

3.1 Failure mode

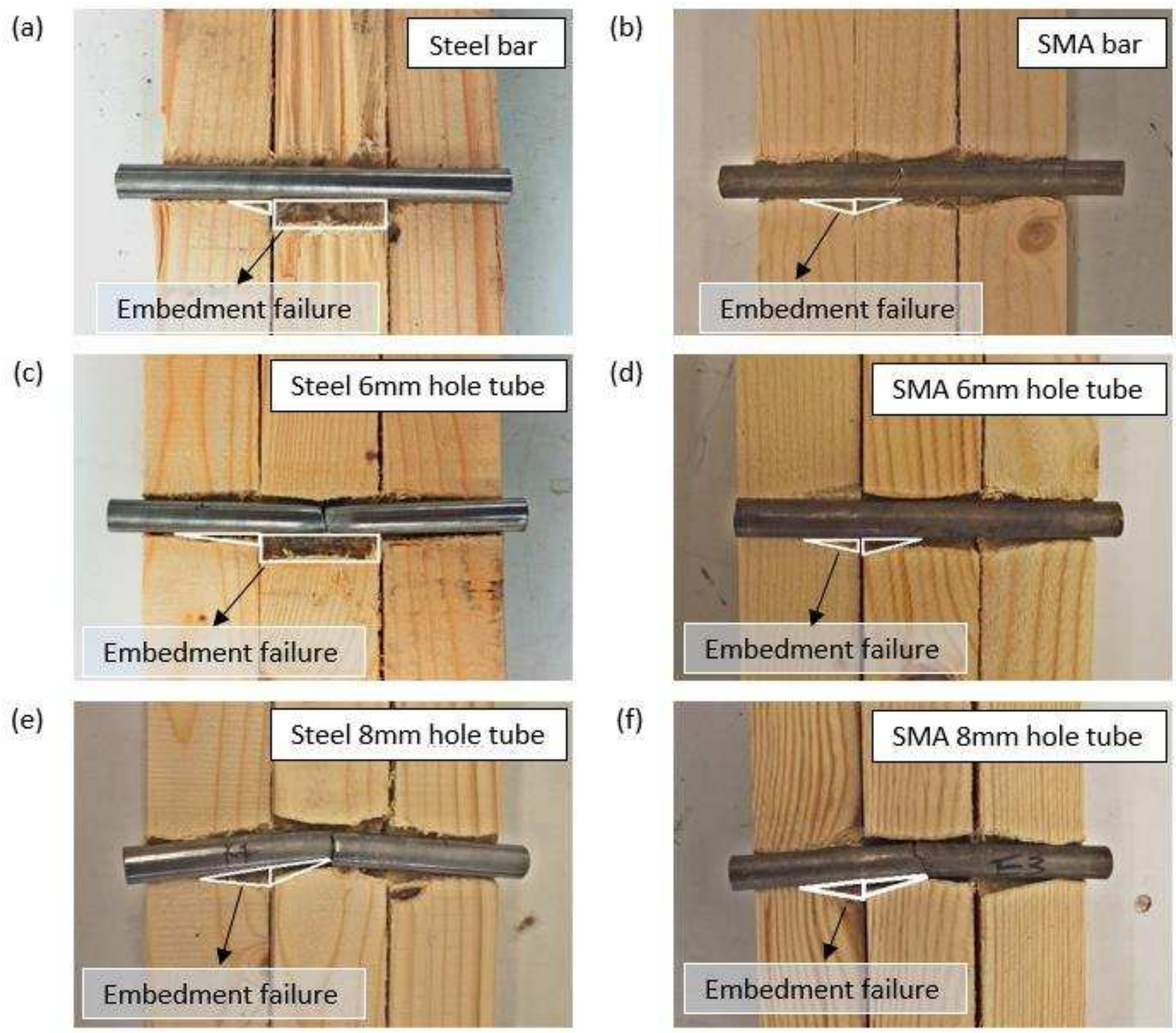


Figure 4 Failure modes for timber connections using (a) steel bar; (b) SMA bar; (c) steel 6 mm diameter hole tube; (d) SMA 6 mm diameter hole tube; (e) steel 8 mm diameter hole tube; (f) SMA 8 mm diameter hole tube;

Figure 4 shows the observations of failure modes. As seen in Figure 4 (a) and (c), which present the transections of connections using steel bars and steel 6 mm diameter hole tubes, the inner timber meets bearing failure and the hole area of that has an elongation of approximately dowel diameter length. Timber splitting failures are also observed in these two types of connections, and were initiated by the embedment failure of the hole area. For connections using steel tubes and SMA dowels, as shown in Figure 4 (b), (c), (d), (e) and (f), the dowels are bent plastically and one plastic hinge occurs in the middle. SMA dowels and steel tubes have lower bending strength and, therefore, bend more easily. As a consequence, the inner timber embedment failures in these samples were smaller. It is noteworthy that steel 6 and 8 mm diameter hole tubes and SMA 8 mm diameter hole tubes were fractured after loading, as thin wall thickness leads to more bending deformation and low-cycle fatigue occurs. In Table 2, the deformations at which each type of connection fails are indicated. It can be found connections with steel receive more damage. For a stronger timber, the embedment failure of timber can be reduced, thus densified veneer wood will be considered to be employed in reinforcing timber connection in further research. Considering dowels with different diameter applied to the connections, the failure mode could be different and Johansen's equations can be referred. In this study, the effect of SMA tubes on failure mode is mainly studied and compared.

3.2 Self-centering behaviours

Load-displacement curves of timber dowel-type connections using mild steel and SMA bars and tubes are presented in Figure 5 and Figure 6, respectively. These two Figures show the last cycle (10th cycle) in each amplitude level. As the connection using a steel bar was broken at 10 mm amplitude, hysteresis at 10 mm and 12 mm amplitude of that does not show in Figure 5. In Figure 6, steel dowel-type connections were broken at 12 mm amplitude. Therefore, SMA allows larger deformation. From Figure 5 and 6, the residual displacement of SMA dowel-type connections is much smaller than that using mild steel. The timber SMA dowel-type connection shows good self-centering effect. The permanent deformation of SMA dowel-type connections is mainly contributed by timber embedment failure. In further studies, the self-centering effect of SMA dowels is expected to be more significant by reinforcing timber in order to increase the embedment strength.

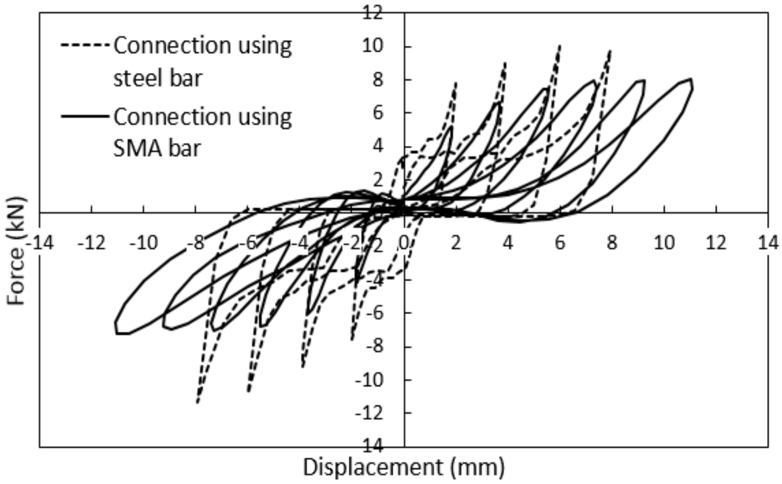


Figure 5 Load-displacement curve of timber dowel-type connections using steel and SMA bar (10th cycle)

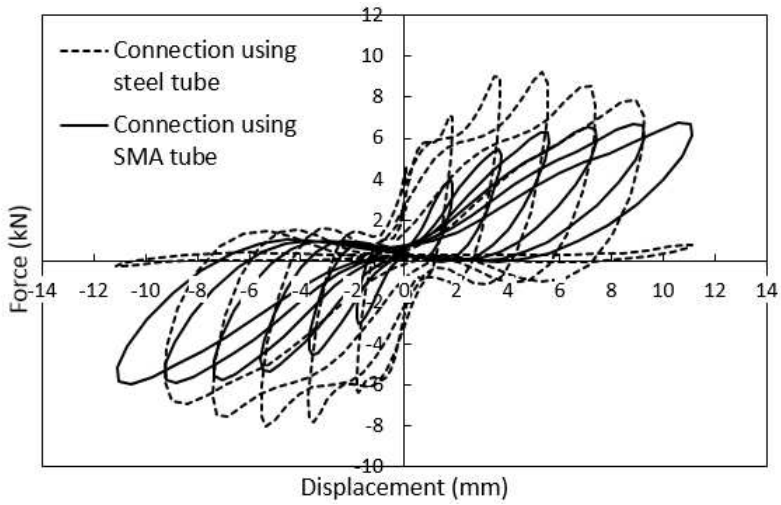


Figure 6 Load-displacement curve of timber dowel-type connections steel and SMA tube (6 mm diameter hole) (10th cycle)

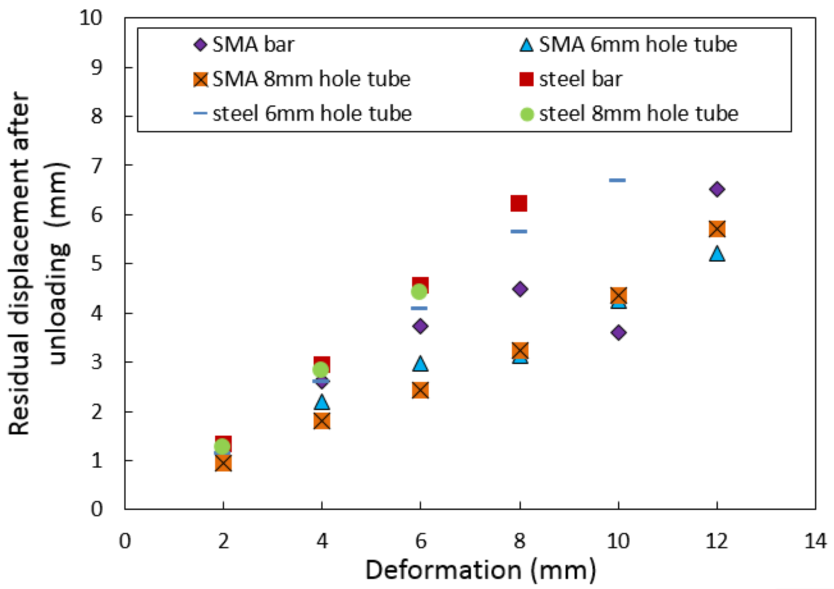


Figure 7 Residual displacement of the SMA and steel dowel-type connections at 10th cycle at each amplitude level

Figure 7 presents the residual deformation in the last cycle at each amplitude level. Since some steel dowel-type connections were broken before completing the loading protocol, in higher displacement levels, residual displacements of these do not show in the graph. In Figure 7, the larger the loading amplitude, the better the self-centering behaviour of SMA dowel-type connections compared with steel dowel-type connections. For instance, at amplitude of 2 mm, the re-centering effect is not obvious, whilst the retrieval is large at amplitude of 10 mm. In SMA bar system, the residual displacement at 10 mm deformation is lower than that at 8 mm deformation; the behaviour could be caused by the self-heating of SMA as higher temperature can facilitate its superelasticity.

In SMA dowel-type connections, using tubes shows better self-centering effect, while this trend is weak in steel dowel-type connections. It is of importance that the self-centering effect of SMA can be developed so as to mitigate the damage of connections and reduce the permanent deformation after earthquakes.

3.3 Damping properties

Damping capacity of connections plays an important role in timber structures to dissipate energy. Equivalent viscous damping ratio (EVDR) of connections in each cycle is calculated based on the methods in BS EN12512 [28]. Comparing EVDR between steel dowels and SMA dowels in Figure 8, steel dowels contribute higher damping and the hysteresis of steel dowel-type connections covers larger area, as seen in Figure 5 and 6. Except for steel 8 mm diameter hole tube connections, EVDR decreases with the increase in loading amplitude.

It is noteworthy that tubes can increase the damping capacity of connections and the larger the hole, the more energy it can dissipate. It can be explained by the fact that tubes are easier to bend plastically and plastic hinges can increase the energy dissipation, as indicated in the Introduction. By converting SMA bars to tubes, the energy dissipation capacity can be comparable with that of a steel bar.

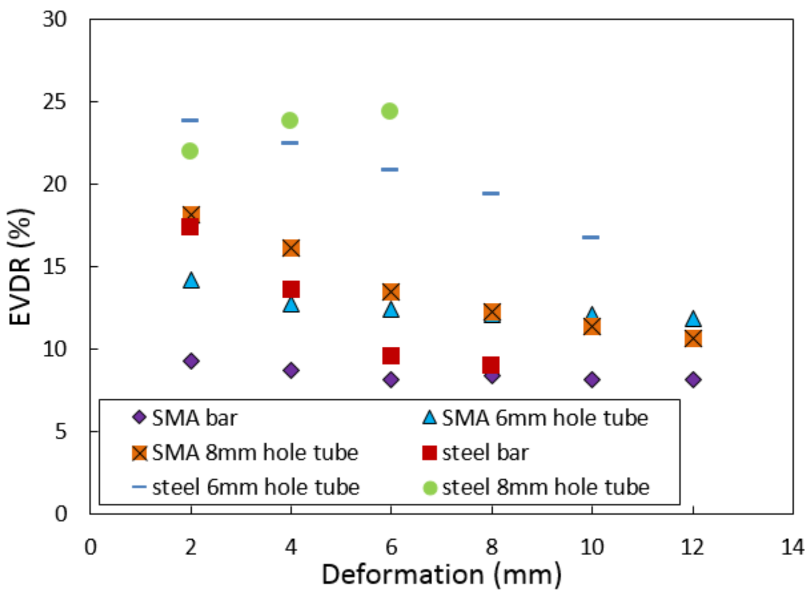
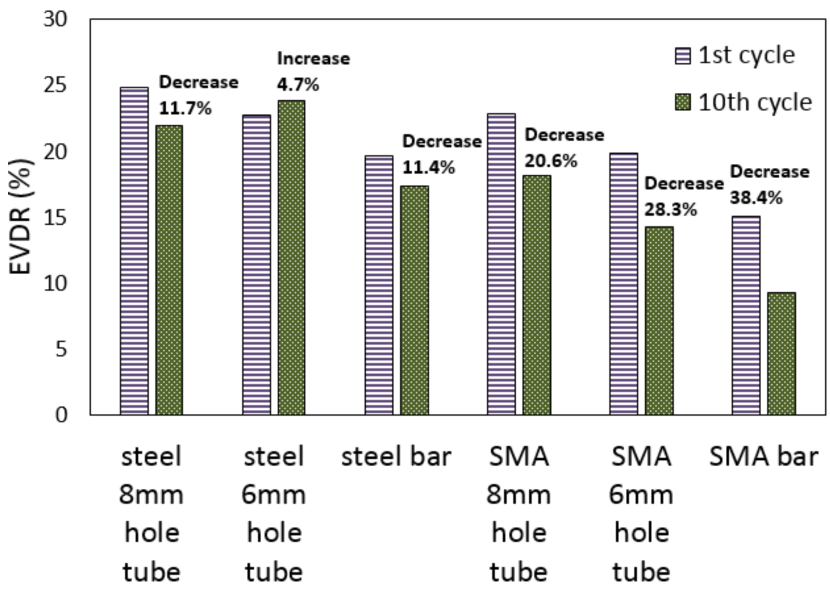


Figure 8 EVDR of the SMA and steel dowel-type connections at 10th cycle in each condition

Figure 9 (a), (b) and (c) compares the EVDR in the 1st cycle and 10th cycle at amplitude of 2 mm, 6 mm and 10 mm, respectively. The variable proportions are presented on each graph. Figure 9 (a) shows how energy dissipation drops down from the 1st cycle to the 10th cycle and the decrement of SMA dowel-type-connections is greater than that of steel. In the first cycle, the damping capacity of timber connections depends on both dowel and timber deformation. After the first cycle, timber often meets bearing failure and only dowel dissipates energy and that is why damping decreases. The larger damping decay in SMA dowel-type connections is caused by microstructural dislocation and slip. The internal stress of SMA contributed by microstructural deformation can facilitate the formation of martensite, which results in the drop of critical yield stress; in the consequence it leads to less energy dissipation [10, 29]. However, this damping decrement tends to be small when the dislocation stabilises, and this phenomenon can be seen in Figure 9 (b) and 9 (c). Figure 9 (b) compares EVDR in the further loading at amplitude of 6 mm; the decrement of damping of SMA dowels tends to be smaller after 10 cycles, whilst the EVDR of steel bar connections decreases greatly and may be due to low-cycle fatigue. In the following loading procedures, as shown in Figure 9 (c), SMA shows little damping decay between the 1st and 10th cycle, while connections using steel bars and steel 8 mm hole tubes are broken. It is notable EVDR compared in study is regarded as from a whole connection even though the damage of the wood is different in each series.

(a)



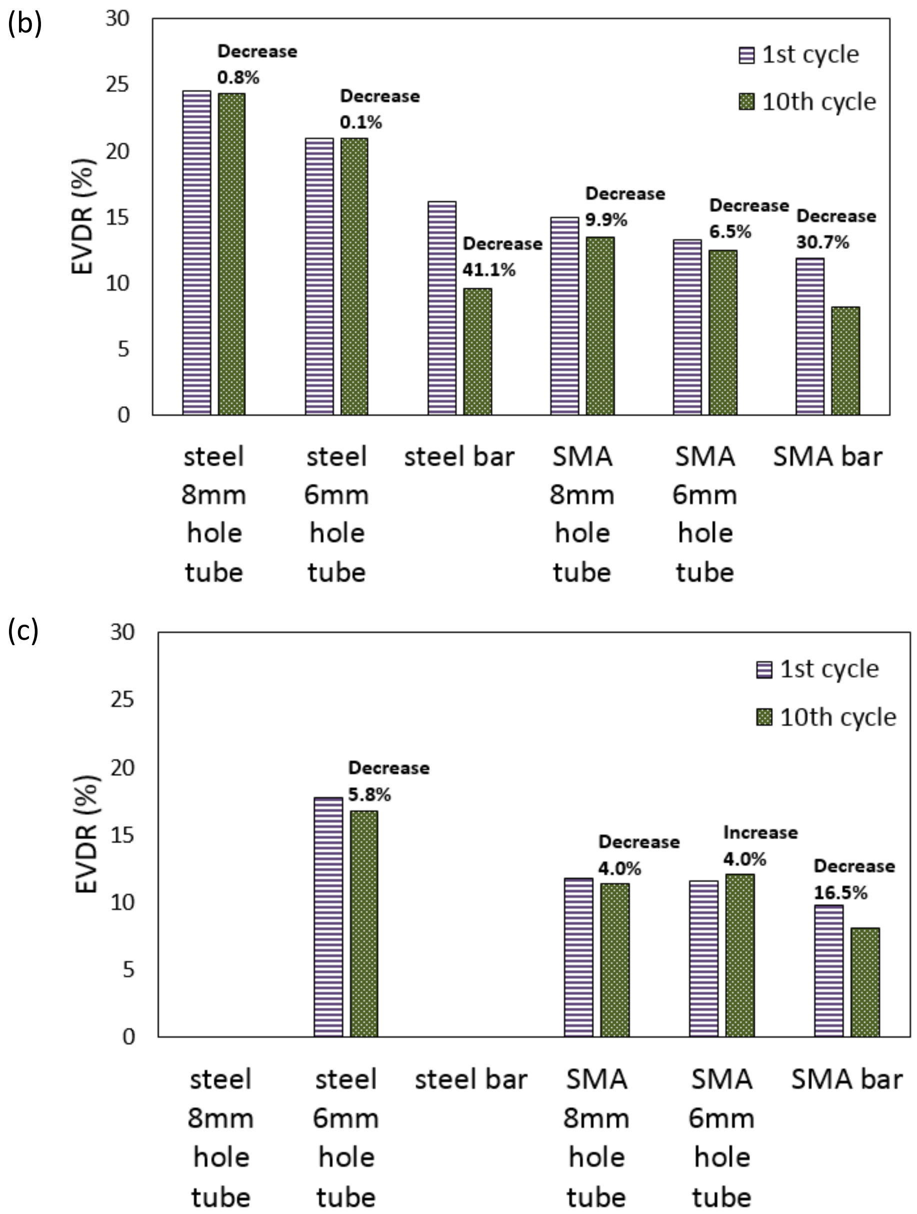


Figure 9 Comparison of the EVDR of the timber dowel-type connection between 1st cycle and 10th cycle (a) at amplitude of 2 mm; (b) at amplitude of 6 mm and (c) at amplitude of 10 mm;

3.4 Strength and ductility

The yield strength of connections is calculated using the approach in BS EN12512 [28] and is shown in Figure 10. Ultimate strength is presented in Figure 11. These values are averaged from 5 repetitions and the error bars show the standard deviation. It can be seen that steel dowels can provide higher strength for 1-2 kN than SMA dowels, except in the condition using 8 mm diameter hole tubes. The yield strength of SMA dowel-type connections is not influenced so much by converting solid bars to tubes, while the yield strength of steel dowel-type connections is reduced by using tubes.

The ductility is calculated by the formula based on BS EN12512 [28]:

$$D = \frac{V_u}{V_y}$$

where V_u is the ultimate slip and V_y is the yield slip. Figure 12 shows the averaged ductility (D) using 5 samples. The ductility of connection using solid SMA bars is the highest. The reason is that steel was fractured before completing the loading protocol and SMA allows larger deformation, as seen in Figure 5. In terms of steel dowels, 6 mm diameter tubes provide higher ductility. As shown in Figure 6, the elastic stiffness of SMA tube dowel-type connections is lower and leads to lower ductility.

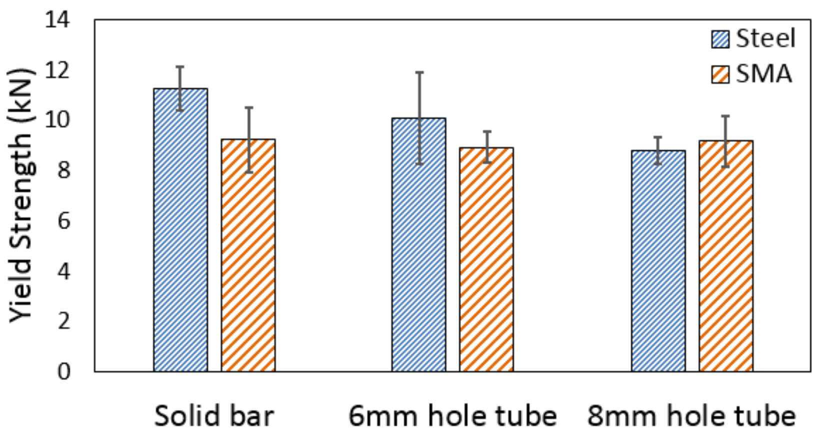


Figure 10 Yield strength of steel and SMA timber dowel-type connections

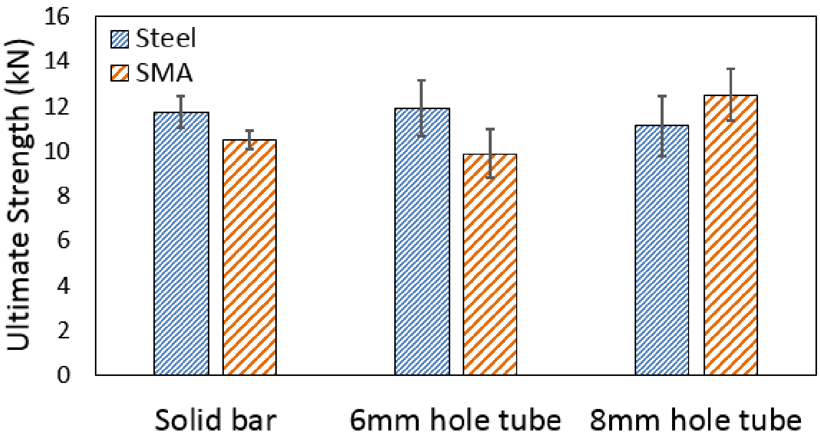


Figure 11 Ultimate strength of steel and SMA timber dowel-type connections

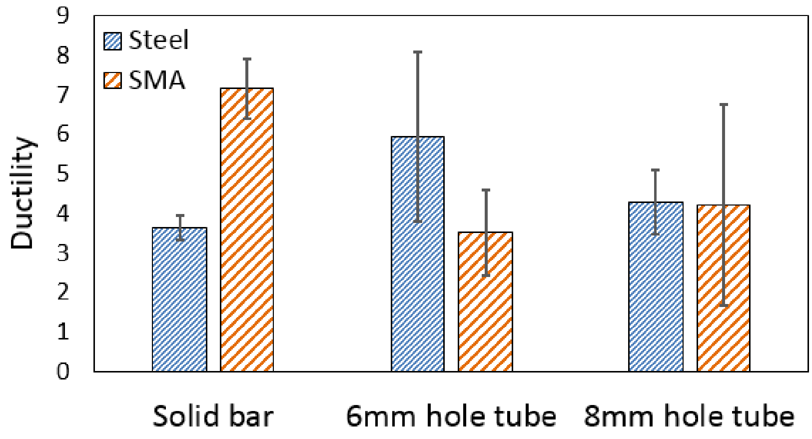


Figure 12 Ductility of steel and SMA timber dowel-type connections

4. Parametric study

As indicated in the previous sections on the mechanical properties of the novel connection, more resilience leads to less damping capacity because of the retrieval of unloading curve. It is of importance to compare the structural dynamic performances between using self-centering connections and using traditional steel dowel-type connections. A parametric study was carried out on a 3-storey timber framed structure as seen in Figure 13. The bay width is 6 meters and the height of each storey is 3 meters. The cross-section dimensions for beams and columns are all 320×200 mm. The Young's modulus of timber used for this structure is 13 GPa. The seismic performances are modelled on the software OPENSEES (Open System for Earthquake Engineering Simulation).

The beam-column connections are modelled using rotational springs as seen in Figure 13. Six types of connections are employed in this study, as shown in Figure 14, and their hysteresis performances are designed to have the features of the tensile connections tested in this study. In Figure 14, connections (a), (c) and (e) represent connections using steel bars, steel 6 mm diameter tubes and steel 8 mm diameter tubes, respectively, while connections (b), (d) and (f) show features using SMA bars, SMA 6 mm diameter tubes and SMA 8 mm diameter tubes, respectively. Connections (b), (d) and (f) have more resilience, less damping capacity and smaller strength. In order to present more energy dissipation when tubes are used, damping capacity is improved in (c) and (d) and more energy dissipation is added in (e) and (f).

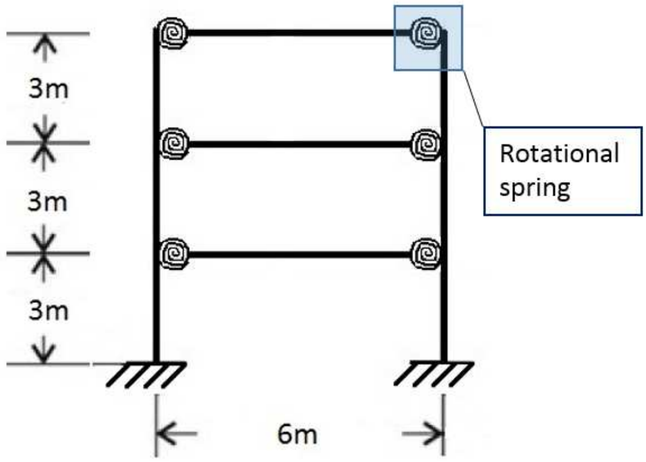


Figure 13 Three-storey timber frame structure model

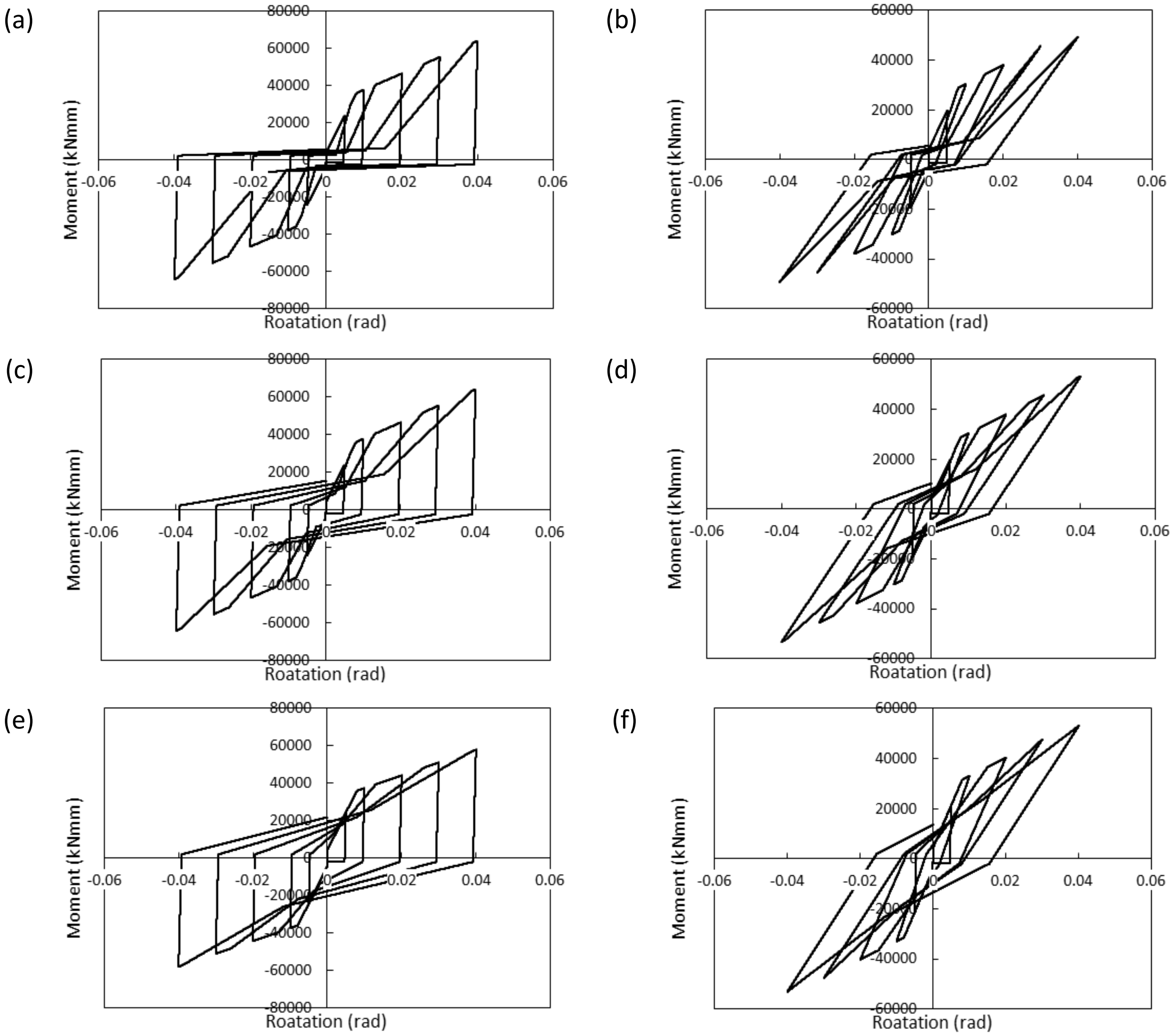
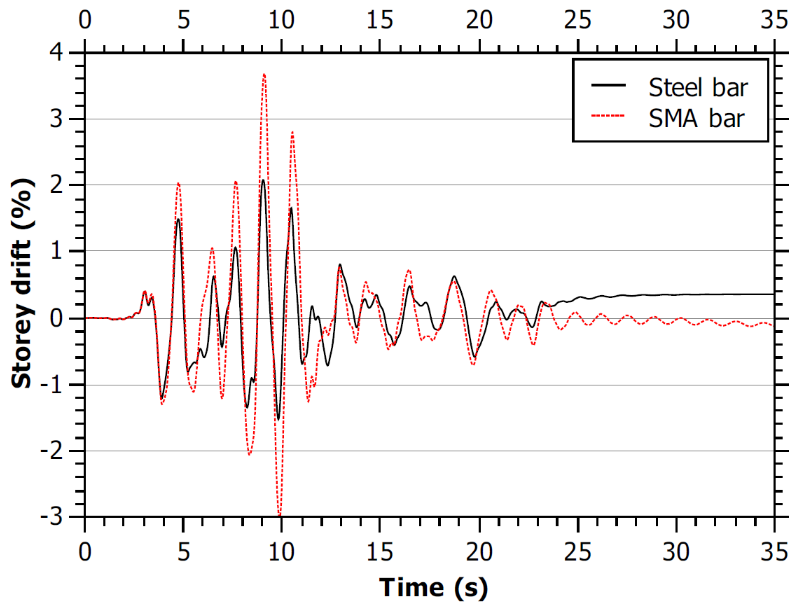
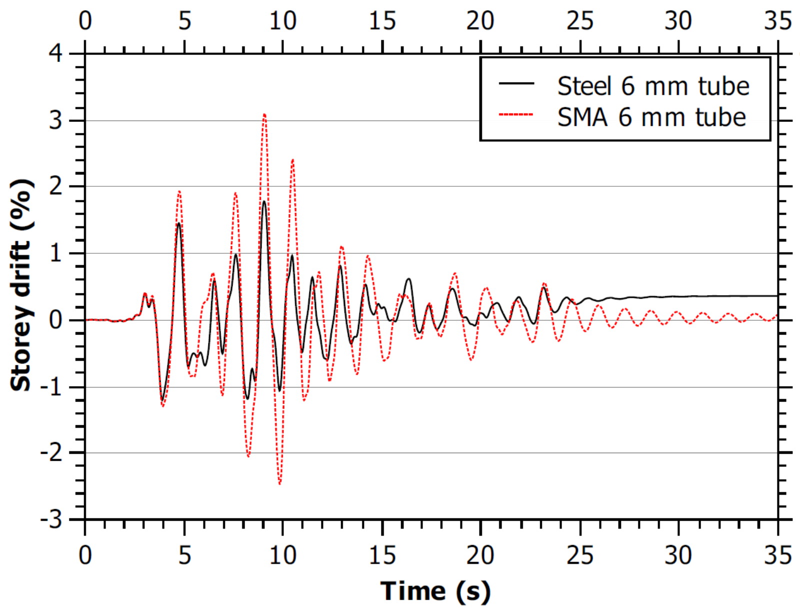


Figure 14 Hysteresis of beam-column connections with the feature of (a) steel bar, (b) SMA bar, (c) steel 6 mm diameter tube, (d) SMA 6 mm diameter tube, (e) steel 8 mm diameter tube and (f) SMA 8 mm diameter tube

(a)


Steel bar
SMA bar
Storey drift (%)
Time (s)

(b)


Steel 6 mm tube
SMA 6 mm tube
Storey drift (%)
Time (s)

(c)

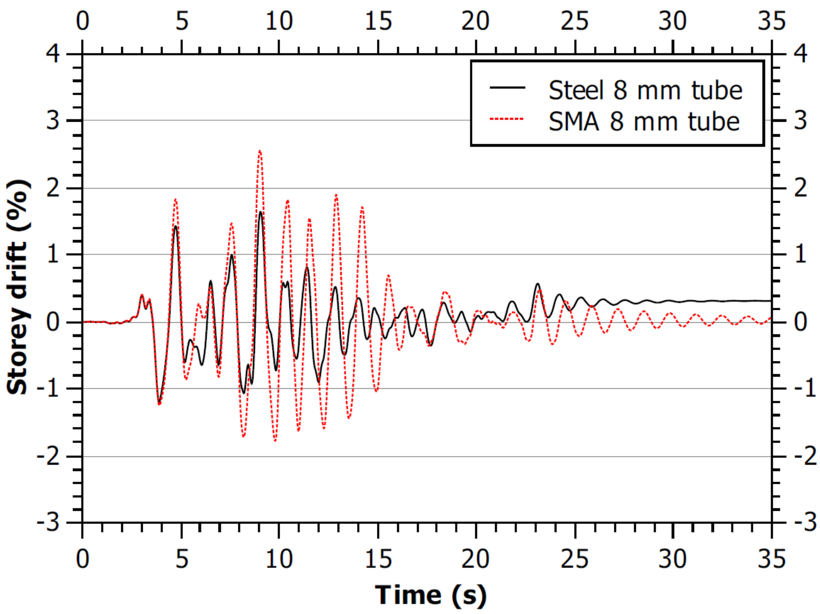


Figure 15 Storey drift results of the timber frame structure subjected to Northridge earthquake (a) using connections with the features of steel/SMA bar; (b) using connections with the features of steel/SMA 6 mm tube; (c) using connections with the features of steel/SMA 8 mm tube

The response of this timber frame subjected to Northridge earthquake (Canoga Park record in 1994) was analysed numerically on OPENSEES. In the first 25 seconds, the earthquake action was input and then the frame vibrates freely for the next 60 seconds. The results in the first 35 seconds are shown in Figure 15. The scaling factor is 1.0 and the PGA of this earthquake wave is 0.41g. Comparing the maximum drift, structures with SMA dowel-type connections have more deformations. By using tubes, the maximum drift can be reduced, which shows that the damping capacity of connections can contribute to the control of maximum drift. The residual drift can be controlled to 0.05% using SMA 8 mm diameter hole tubes; much smaller than 0.36% using steel bars and steel 6 mm diameter hole tubes and 0.32% using steel 8 mm diameter hole tubes, which show that SMA has good self-centering effect.

In summary, satisfactory damping capacity is able to control the maximum drift of structure during earthquakes, and self-centering effect can greatly reduce the residual drift after earthquakes. Both of these two capacities are important, and the design of SMA-based connections should find the balance. In order to increase damping, the application of SMA tubes to connections has the potential and needs further studies.

5. Conclusion

In this study, novel timber connections using SMA solid bars and SMA tubes as dowels are investigated. With regard to performance under earthquake, the connections were tested under dynamic cyclic loadings at between 2 and 12 mm amplitudes. SMA dowel-type connections show good self-centering effect compared with steel dowel-type connections and can effectively reduce residual deformation, especially at a larger displacement level in which SMA tubes present better self-centering properties. Timber connections with steel have more damping than with SMA, however, receive more damage. The energy dissipation capacity of SMA dowel-type connections is found to be improved by applying thinner-wall-thickness tubes. The equivalent viscous damping ratio decay in the first cycles is observed both in steel and SMA. Decrement in SMA is more, but tends to stabilise. The strength of steel dowel-type connections is relatively higher except in the condition using 8 mm diameter hole tubes. It is noteworthy that the application of SMA tubes to timber connections shows better self-centering effect, higher damping and comparable strength with steel.

Both self-centering and damping capacities of connections play an important role in structural seismic performance control, according to the parametric study on a 3-storey timber framed structure. More resilience in the connections greatly reduces residual deformation after earthquakes, while damping can reduce the maximum drift during earthquakes. Future SMA dowel-type connection design should discover the appropriate balance. The novel SMA tube dowel-type connection investigated in this study has the potential to strike the balance, but needs more research in terms of its ductility and fatigue.

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Table 1 Test protocol

Test number	Material of the dowel	Dowel dimensions: diameter of the hole (mm)	Repetition number
1	Cu-Al-Mn SMA	0 (Solid bar)	5
2		6	5
3		8	5
4	Mild steel	0 (Solid bar)	5
5		6	5
6		8	5

Table 2 Failing deformation of each type of connection

Test number	Material of the dowel	Dowel dimensions: diameter of the hole (mm)	Failing deformation (mm)
1	Cu-Al-Mn SMA	0 (Solid bar)	Did not fail
2		6	Did not fail
3		8	12
4	Mild steel	0 (Solid bar)	10
5		6	12
6		8	8

Dear Editor,

Please find the table below which we respond to the comment that the first reviewer has, we have considered the comment from the reviewer, responded and amended our manuscript as appropriate. The reviewers' efforts and time are much appreciated. We are looking forward to working with you during the review process.

Best regards,

Wen-Shao Chang

1st Reviewer's comment	Response to reviewer
This manuscript went to my attention: Earthquake Engineering and Engineering Vibration September 2007, Volume 6, Issue 3, pp 259–268 Nonlinear aspects of energy dissipation in wood-panel joints DOI: 10.1007/s11803-007-0764-9 I guess it must be cited in this paper.	We have read this journal paper, and we think it is very useful to be cited. We have cited it in the section of Introduction.