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MONOTONIC TESTING OF BRACE ASSEMBLIES FOR PIPING SYSTEMS AND CONSIDERATIONS FOR CAPACITY DESIGN

Muhammad Rashid[1], Rajesh P. Dhakal[2] and Timothy J. Sullivan[3]

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ABSTRACT

Distributed nonstructural elements (NSEs), such as piping systems, are restrained against seismic actions using proprietary or, at times, custom-designed braces. The strengths of these elements are provided in the component brochures published by the manufacturers, with no information on their deformation capacities. Previous research on the seismic performance of NSEs provide several formulations to calculate possible reductions in design force by relying on ductility capacity of their seismic restraints. However, designers require a realistic estimate of the ductility capacity of the seismic restraints to use these formulations. This paper discusses the results of a test program on the behavior of brace assemblies under monotonic tensile and compression loading. The results are used to identify the potential failure modes of the tested brace assemblies and to quantify their ductility capacity. Further, design examples are presented to highlight the need for the use of capacity design principles in the design of brace assemblies and their anchors.

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INTRODUCTION

Piping systems are supported using hanger rods and braces to resist gravity loads and seismic demands, respectively (Figure 1). These support systems are usually proprietary, i.e., these are produced by different companies with different geometrical and attachment details. Braces are usually an assembly of three components: i) brace element (e.g., hollow circular or channel section), ii) building-attachment component (BAC) and, iii) pipe-attachment component (PAC); these are illustrated in Figure 2. The attachment components are tested according to standard approval procedures for assignment of load ratings (strength) [1,2]. To the knowledge of the authors, these procedures do not quantify the post-yield deformation capacity of the components nor do they investigate their likely failure mechanisms, though the testing procedures include subjecting the braces to multiple cycles of loading.

Such information is necessary to determine if there is any ductility inherent in the design of these components. New Zealand standards addressing the seismic design of non-structural elements allow reductions in the design force by relying on the ductility capacity of their seismic resisting elements [3,4]. Research has shown that seismic demands on acceleration-sensitive NSEs can be significant if resonance occurs between the supporting structure and the components attached to its floors [5–9]. Such demands can be reduced for the purpose of design by utilizing the ductility capacity of seismic restraints using empirical relationships between acceleration or force demand and ductility capacity [10]. However, such relationships can only be utilized reliably if the ductility capacity of the braces is provided by manufacturers.

Moreover, load ratings are assigned to attachment components through testing. The capacity of brace elements, being of known geometry and materials, can be manually calculated. This implies that the design procedure would primarily involve i) comparison between the brace design force and the load rating of a chosen system (attachment components) and ii) the design of anchors for the anticipated demands. It is, however, not clear as to what is usually the difference between the calculated design force and the actual capacity of a chosen system since the rated capacities incorporate safety factors. Such differences between the calculated design force and the actual capacity of a chosen system has implications for the failure mode of a brace assembly and the anchor, which connects it to the supporting structure.

(a) Rigid braces. ***(b) Cable braces.***

Figure 1: Different types of braces supporting sprinkler piping systems.

The strength of a typical brace element (e.g., hollow circular or channel section) is usually considerably higher than the load ratings of typical attachment components. For example, for a 25mm pipe section, the tensile yield strength is 98.12kN considering steel yield strength to be 320MPa, whereas a review of typical attachment components reveals that their capacities are smaller than the typically used brace elements. Further, based on some calculations, and expert opinion, it has been found that the

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[1] *Design Engineer, Silvester Clark, ce.rashid@gmail.com (Member)*
[2] *Professor, University of Canterbury, Christchurch, rajesh.dhakal@canterbury.ac.nz (Fellow)*
[3] *Professor, University of Canterbury, Christchurch, timothy.sullivan@canterbury.ac.nz (Member)*

capacities of anchors can also be much smaller than the strengths of typical brace elements, especially considering the anchor capacity under simultaneous tension and shear. This means that in a seismic event, if the demand exceeds the design force, the failure will most likely occur in the anchors, if the difference between the calculated design force and the actual capacity of the chosen attachment component is significant. Failure of anchors will occur because the attachment components will not yield at the design force nor the brace element. The authors regard anchor failure as an undesirable failure mode because of its brittle nature.

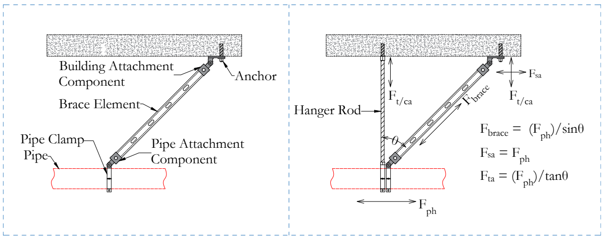


Figure 2: Different elements of a typical brace assembly.

From the above discussion, two major research questions have been identified with regard to the seismic performance of brace assemblies:

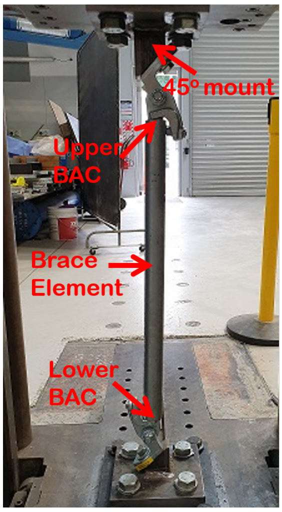
1. *What are the likely failure modes of typical brace assemblies used in NZ?*
2. *What is the likely failure hierarchy within the brace assemblies?*

To answer the research questions above, the authors conducted an experimental campaign to obtain force-deformation characteristics of different piping brace assemblies used in NZ under monotonic tensile and compression loading. These tests were conducted to identify the likely failure mechanisms of different brace assemblies (including brace elements and the attachment components), and to assess their post-yield deformations. Further, the tests provide evidence on the strength hierarchy within a brace assembly, between the attachment components and the brace elements, for capacity design considerations. Based on the test results, design examples are discussed to emphasize the need for consideration of capacity design principles in designing such brace assemblies. Filiatrault *et al.* [11], Peronne *et al.* [12] and Shang *et al.* [13] have conducted testing on different bracing types to study their cyclic behaviour, however, the bracing types and the performance metrics studied are not directly aligned with the research questions addressed in this paper.

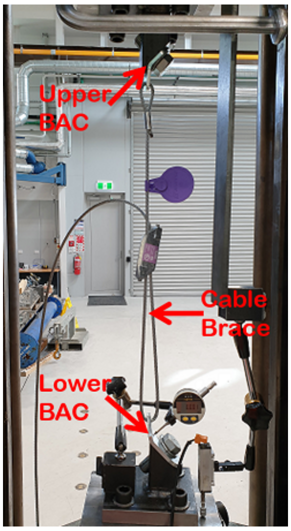
TEST MATRIX AND SETUP

The test matrix consisted of four variants of piping brace assemblies. The first three variants were rigid brace assemblies with the brace element being a pipe or channel section; the fourth variant was a cable brace assembly with the brace element being cables of different diameters. The cross-sectional dimensions of the tested brace elements are given in Table 1.

In all the cases, the brace elements were 500mm long. For the rigid brace assemblies, the PACs and BACs were tested separately to characterize their individual performances, i.e., the specimens consisted of a brace element with either the building-attachment or pipe-attachment component on both ends as shown in Figure 3a. The cable brace assemblies were tested as a whole, with each specimen consisting of a pipe and building-attachment component on the opposite ends as shown in Figure 3b. This was done because the attachment components were nondetachable.



(a) Test setup for rigid brace assemblies.



(b) Test setup for cable brace assemblies.

Figure 3: Test setup for different tested components.

The test setup consisted of two base plates mounted to the upper and lower jaws of the test machine. The plates had a mount for the BACs with an inclined surface at 45^o to represent the inclination of a brace in an actual piping system. For the PACs, a 65mm pipe section was welded to two plates that were welded to the base plate. The specimens were tested at a loading rate of 0.5mm/s. The test matrix consists of a total of 47 specimens.

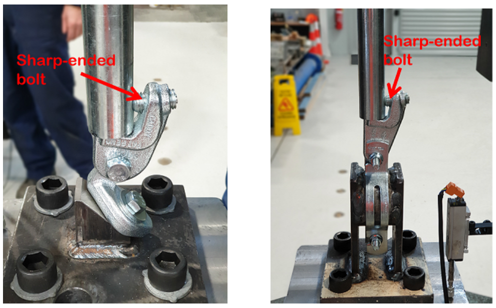
For variant 1, the building-attachment and pipe-attachment components were connected to the brace element using a sharp-ended bolt that had to be turned to a specific torque which was indicated by the coming off of the bolt cap (Figures 4a and 4b). Upon turning, the bolt pierced into the wall of the pipe section, forming a connection between the attachment and the brace element. For variant 2, the attachment components consisted of a hinge that was attached to the brace element using a spring nut as shown in Figures 4c and 4d. The spring nut had to be slid under the two edges of the channel section and then the hinge would be

Table 1: Cross-sectional dimensions of brace elements used in different variants.

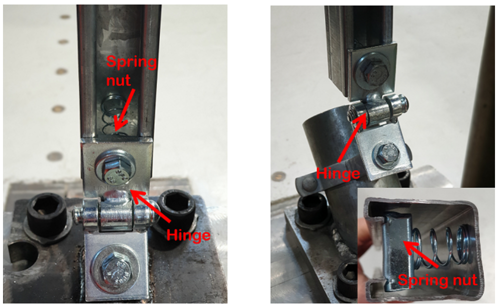
Specimen	Brace Element	Dimensions (*mm*)
Variant 1	Hollow circular	33.7^a, $t^b = 3.2$
Variant 2	Channel section	41 x 41 x 1.6
Variant 3	Channel section	21.5 x 41.3 x 1.5
Variant 4	Cable	2^c, 3, 4.75 & 6

a = outer diameter; b = wall thickness; c = cable diameter.

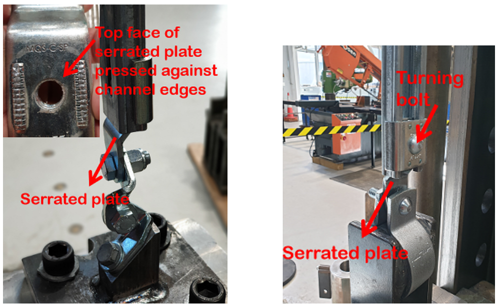
bolted to the spring nut that would press the serrated face of the spring nut against the channel ends to form a connection with the brace element. The variant 3 attachment components consisted of a serrated plate which had to be slid under the edges of the channel section. Once in place, the bolt on the attachment component had to be turned to a certain torque which was indicated by the coming off of the bolt cap. These details are shown in Figure 4e and 4f. The components of cable brace assemblies were pre-assembled and are identified in Figure 5.



(a) BAC - Variant 1 *(b) PAC - Variant 1*



(c) BAC - Variant 2 *(d) PAC - Variant 2*



(e) BAC - Variant 3 *(f) PAC - Variant 3*

Figure 4: Components of tested rigid brace assemblies.

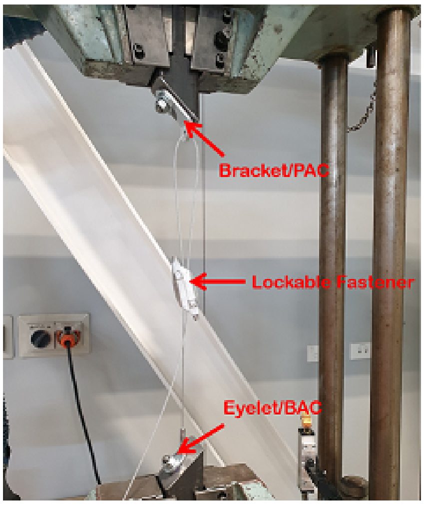


Figure 5: Components of tested cable brace assemblies.

RESPONSE OF SPECIMENS

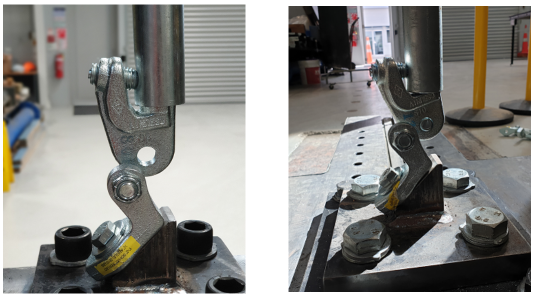
This section discusses the force-deformation characteristics of the tested brace assemblies. It is important to note that behaviour under compression would be different for cases with brace elements shorter or longer than the 500mm brace elements used in these tests. The same consideration does not apply to tension as in all the cases no visible elongation was observed in the brace elements and failure was concentrated in the attachment components except the cable brace assemblies where failure occurred in the cable. These observations are further discussed below. Recorded values of force and deformation obtained from the testing for different variants are tabulated in the appendix.

Variant 1 - BAC

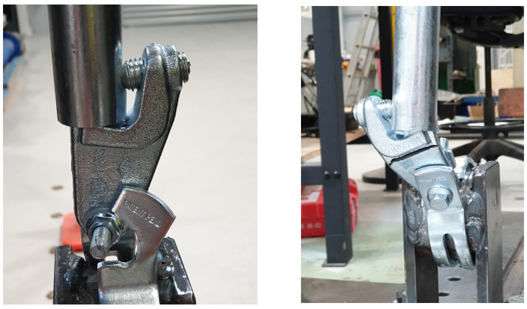
The specimens failed with a shear failure in the bolt both under tension and compression loading as shown in Figures 6a and 6b. As indicated by the force-deformation responses in Figure 7a, the failure was sudden and brittle. The average strengths under tension and compression were 23.8kN and 25.3kN, respectively.

Variant 1 - PAC

The PAC had similar connection to the brace element as the BAC and failed in different modes under tensile and compression loading. Under tensile loading, the pipe clamp edge around the bolt deformed and eventually detached from the bolt as shown in Figure 6c. Under compression, the pipe clamp rotated, which caused bending in the attachment component leading to fracture (Figure 6d). The force-deformation responses in Figure 7b do not indicate a sudden failure under tension and compression but were characterized by degradation in strength post-yield. The average strengths under tension and compression were 15.5kN and 24.5kN, respectively.

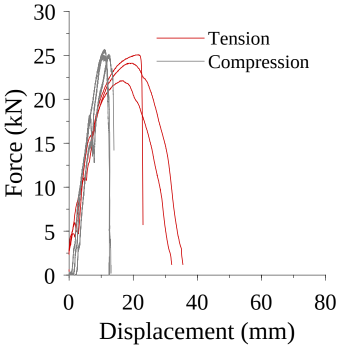


(a) BAC-T *(b) BAC-C*

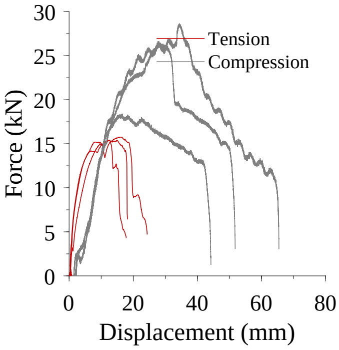


(c) PAC-T *(d) PAC-C*

Figure 6: Failure modes of variant 1.



(a) BAC.



(b) PAC.

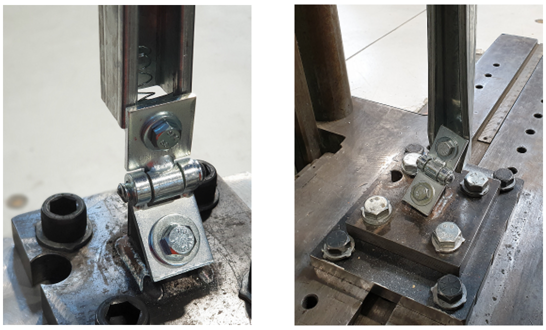
Figure 7: Force-deformation response of variant 1 components under monotonic tensile and compression loading.

Variant 2 - BAC

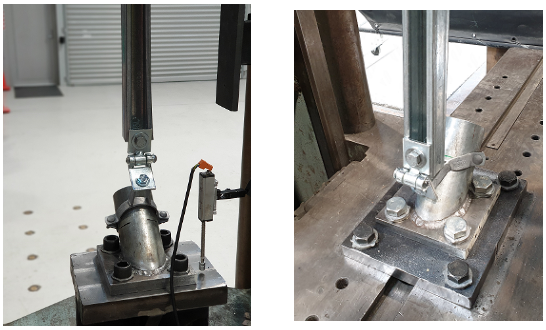
The failure mode under tension and compression essentially consisted of detachment of the hinge from the brace element due to sliding of the spring nut and the hinge along the brace element as shown in Figures 8a and 8b. However, under increasing compression load, the hinge pressed against the channel section and deformed the channel section until finally the spring nut dislocated. The force-deformation responses in Figure 9a do not indicate a sudden and brittle failure but were characterized by degradation in strength post-yield. The average strengths under tension and compression were 7.7kN and 11.2kN, respectively.

Variant 2 - PAC

The failure mode under tension was the detachment of the hinge from the brace element due to sliding of the spring nut similar to the BAC. Some elongation in the pipe clamp was also observed as shown in Figure 8c. Under compression, the pipe clamp bent until it touched the pipe and nothing actually failed as shown in Figure 8d. The force-deformation responses in Figure 9b show a sudden failure under tension, whereas the bending of the clamp under compression provides some deformation capacity. The average strengths under tension and compression were 7.5kN and 4.7kN, respectively.

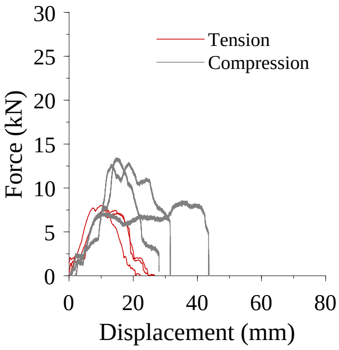


(a) BAC-T. *(b) BAC-C.*

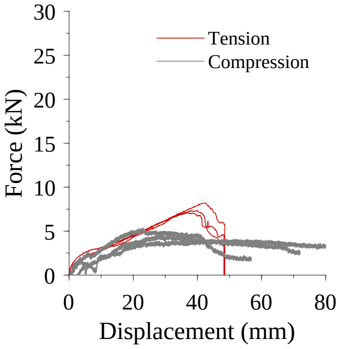


(c) PAC-T. *(d) PAC-C.*

Figure 8: Failure modes of variant 2.



(a) BAC.

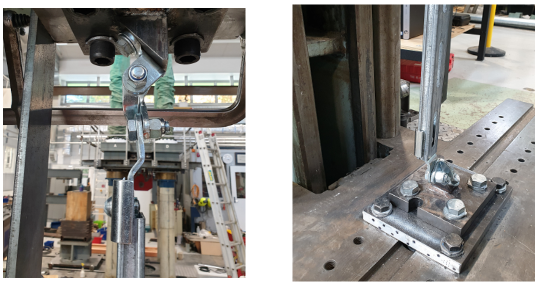


(b) PAC.

Figure 9: Force-deformation response of variant 2 components under monotonic tensile and compression loading.

Variant 3 - BAC

The failure mode of the BAC under tension was detachment from the brace element due to the slippage of the serrations that formed the connection between the component and the brace element (Figure 10a). Under compression, the component simply rotated under the application of the load and thus could not be tested to see any mechanical damage as shown in Figure 10b. The force-deformation responses in Figure 12a show that the response under tension was brittle; the response under compression could not be assessed due to rotation of the component. The average strength under tension was 17.9kN.



(a) BAC-T *(b) BAC-C*

Figure 10: Failure modes of BACs in variant 3.

Variant 3 - PAC

The failure mode of the PAC under tension was the slippage of the serrations and hence detachment from the brace element. Under compression, the brace element buckled as shown in Figures 11a and 11b. The response was brittle both under tension and compression as shown in Figure 12b. The average strengths under tension and compression were 23.3kN and 23.7kN, respectively.

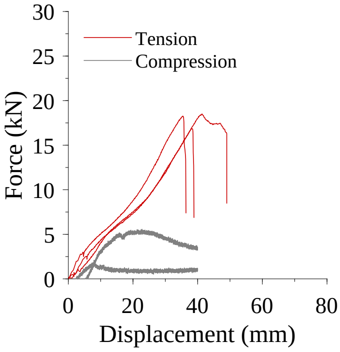
Using Euler's critical load formula, the theoretical compression capacity of the brace element with a clear length of 406mm (accounting for the attachment component on both ends) and a modulus of elasticity equal to 200,000MPa, equals 110kN and 440.2kN for ends pinned and fixed, respectively. Both idealizations of the boundary conditions significantly overestimate compression capacity.

The moment of inertia used in these estimations was taken from the component catalog published by the manufacturer with a reported value of 9200mm^4. A close look at the buckled shape shows that the buckling occurred near the opening in the channel element where the cross-sectional dimensions were not the same as other parts of the section (Figure 11b). Such openings in channel sections are common for installation purposes and should be considered while estimating the capacity of brace elements under compression.

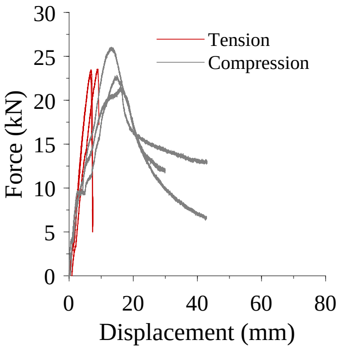
(a) PAC-T

(b) PAC-C

Figure 11: Failure modes of PACs in variant 3.



(a) BAC.



(b) PAC.

Figure 12: Force-deformation response of variant 3 components under monotonic tensile and compression loading.

Variant 4 - Cable

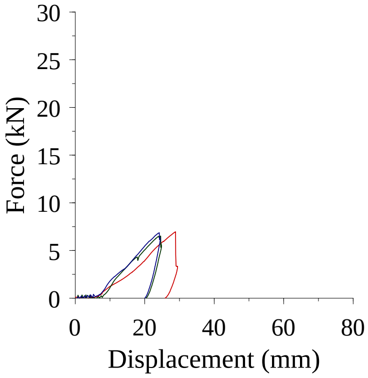
Cable braces with diameters of 2.0mm, 3.0mm, 4.75mm and 6.0mm, were tested under monotonic tension. The testing showed that the behavior of the cable braces with different diameters was similar. At the beginning of the loading, the specimens exhibited some slack due to looseness in different parts of the assembly. It was observed that the slack reduced with increase in diameter of the braces as shown by the force-deformation plots in Figure 14 for 3mm and 6mm cables.

Post the slack, the specimens exhibited almost linear behavior. It is essential to note that both attachment components deformed under the applied load. The force-deformation response includes the deformation from the bracket and the eyelet. No slip of the cable through the lockable fastener was observed in any of the specimens.

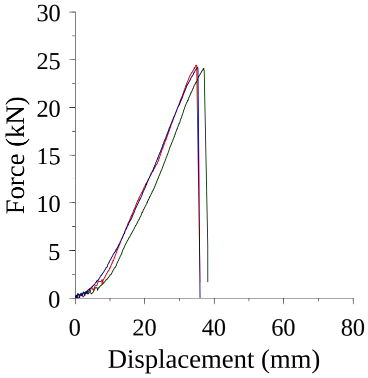
Damage was only concentrated in the cable either in the loop around the bracket hole or near the grips of the lockable fastener as shown in Figure 13 as typical cases. Fracture of the cable constituted the failure mode in all the specimens as can be identified by the steep and sudden reduction in strength (see Figure 14). The average strengths of 2mm, 3mm, 4.75mm and 6mm cables were 3.4kN, 6.8kN, 16.2kN and 24.2kN, respectively.

(a) Damage near the grips. *(b) Damage around the bracket.*

Figure 13: Typical damage in cable braces concentrated near the grips of the lockable fastener and around the holes in the brackets.



(a) 3mm cable.



(b) 6mm cable.

Figure 14: Force-deformation response of cable brace assemblies under monotonic tensile loading.

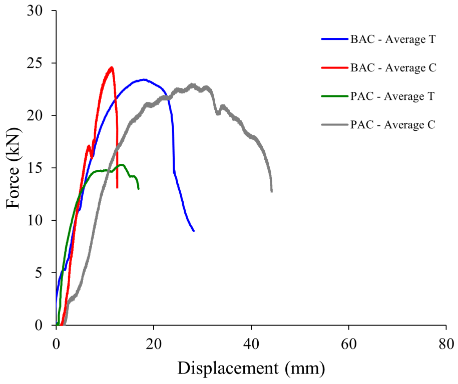
DESIGN RECOMMENDATIONS

This section provides an assessment of the post-yield deformation capacity of the brace assemblies from a perspective of reducing their design forces. The capacity to exhibit stable post-yield response in line with traditional seismic design philosophy was not observed in any specimen except to some extent in the PACs of variants 1 and 2 due to the elongation and/or opening of the pipe clamps. In all other cases, the deformation modes were such that a stable post-yield response could not have been formed. However, the ability to deform, buckle, rotate, slip and twist with increasing load without fracture was observed in the all specimens with increasing load except the BAC in variant 1.

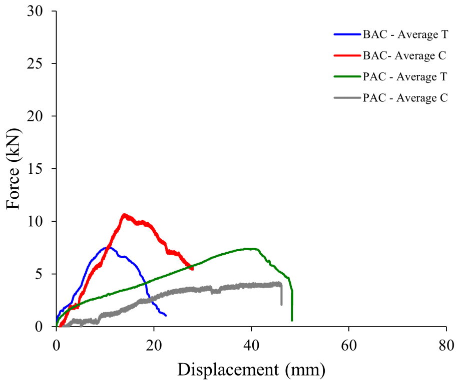
It has been argued in literature that such deformations could cause a reduction in the instantaneous peak acceleration demands [14]. In some cases, such as the BAC in variant 2, the bending of the hinge was even sustained for some time before the complete slip of the nut. Based on this discussion, Table 2 recommends nominal ductility values for the tested variants along with comments to justify the assigned values. These values could be used in design until a more robust assessment of the ductility capacity of these systems is undertaken under static-cyclic loading. The ductility values in Table 2 are supported by the test data as summarized in Figure 15.

Table 2: Recommended values of ductility capacity for the tested brace assemblies.

Bracing	Ductility (μ)	Comments
Variant 1	1.25	Deformation in the pipe clamp
Variant 2	1.25	Deformation of the hinge and pipe clamp
Variant 3	1.0	Needs further testing
Variant 4	1.0	Sudden failure of cable



(a) Variant 1.



(b) Variant 2.

Figure 15: Average responses of BACs and PACs from all the tests for variants 1 and 2.

It can be seen that the BACs or the PACs could individually have larger deformation capacities under tension or compression, such as the PAC in variant 01 under tension and compression. However, in an actual earthquake, a brace assembly will be subjected to alternating tension and compression and will have force and deformation in both the BAC and the PAC. Thus, any allowance for ductility should consider both components and also tension and compression forces.

In variant 01, the average strengths of the BAC and PAC are approximately equal under compression but the BAC has a brittle response. Under tension, PAC has lower strength and also higher deformation capacity, however this does not warrant a higher ductility value as the response of the assembly under compression is brittle. Similar consideration applies to variant 02, where the PAC with lower strength has some deformation capacity under compression; however, the BAC under tension has a brittle response, and a high value of ductility does not seem appropriate. Due to these reasons, and the fact that no stable ductile responses were formed, the authors believe that the values in Table 2 are appropriate until more comprehensive test data becomes available from static cyclic loading on complete brace assemblies with both the BAC and the PAC in the same specimen.

FAILURE HIERARCHY & CAPACITY DESIGN CONSIDERATIONS

Rashid *et al.* [6] includes a detailed discussion on the need for capacity design of brace assemblies and the relevant design approach. Here, the results from testing are used to support the arguments made in Rashid *et al.* [6] in favor of capacity design. First, the testing reveals that in all the rigid brace assemblies, except for variant 3 with PACs under compression, failure or damage was confined to the attachment components and nothing of significance happened in the brace elements. This confirms the observation that brace elements are stronger than the attachment components, though this strength hierarchy will also be dependent on the length and cross sectional details of the brace elements.

For variants 1 and 4, the average of the test capacities and the rated capacities reported in the catalogs published by the manufacturers are compared in Table 3. For variant 1, only the tensile capacity of the PAC could be compared as information on other capacities are not given in the catalogs. The test capacities provide an estimate of the actual capacities of the brace assemblies. Table 3 also shows the differences between the test and rated capacities for the different variants with the maximum difference being 7.5kN for variant 4 with a cable diameter of 6mm, which corresponds to an overstrength of 1.5. Herein overstrength quantifies the difference between the two capacities and not the typically employed concept of increase in strength beyond yield. The differences between the two capacities are due to the use of strength reduction factors as safety factors in the values reported in the published catalogs. The purpose of this comparison is to emphasize the need for consideration of the overstrength inherent in these components which might lead to undesired failure modes. This is explained below through an example, based on some necessary assumptions, with the aim to highlight the importance of capacity design. The presented example is for the sole purpose of highlighting the importance of capacity design and should not be considered a robust design exercise.

Consider a hypothetical piping system with a layout shown in Figure 16. The braces on the distribution pipe, 500mm long, are assumed to be connected to the supporting floor using post-installed anchors at an angle of 45°. The piping system is supposed to be subject to horizontal seismic floor excitation that

Table 3: Comparison of test and rated capacities of bracing variants 1 and 4.

Bracing	Test capacity (*kN*)	Rated capacity (*kN*)	Difference (*kN*)	Overstrength
Variant 1	15.5	13.6	1.9	1.14
Variant 4 (2mm)	3.4	1.3	2.1	2.6
Variant 4 (3mm)	6.8	2.2	4.6	3.1
Variant 4 (4.75mm)	16.2	8.8	7.4	1.8
Variant 4 (6mm)	24.2	16.7	7.5	1.5

results in a peak pipe acceleration of 3.60g, which is arbitrarily chosen from NZS 4541. Using the guidelines for seismic tributary mass in NZS 4541, the axial force demand in the middle brace is calculated to be 8.7kN, and is assumed to be the design force. The brace anchor was designed, using a design software, for simultaneous application of tensile and shear force of 6.2kN, resulting from the brace force demand of 8.7kN (see Figure 2 for relationship between brace and anchor force). Since the software calculated the required anchor size for a demand of 6.2kN using various safety factors, the actual anchor capacity will be larger than 6.2kN. Here, the actual capacity of anchor is presumed to be 1.5 times 6.2kN, which would result result in a value of 9.3kN.

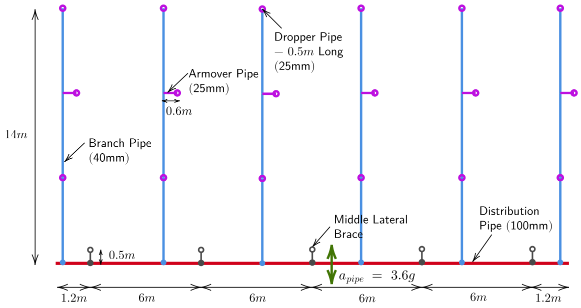


Figure 16: Hypothetical sprinkler piping system.

For this system, bracing variant 1, and variant 4 with 4.75mm and 6.0mm cables, can be used to satisfy the design force demand based on the rated capacities reported in Table 3. The differences between the rated capacities and the brace design force are 4.9kN, 0.10kN and 8.0kN for variant 1 and variant 4 with 4.75mm and 6.0mm cables, respectively. All three available options can be used to brace the piping system based on a comparison with the design force, and the three options offer different levels of safety against failure if the design force is exceeded. However, these are rated, and not the actual capacities, and in reality the factor of safety against brace failure in case of design force exceedance could be larger, which will have implications for anchor failure. If the design force of 8.7kN is exceeded, the anchor would fail first as its presumed actual capacity of 9.3kN is less than the test capacities (estimated actual capacities) of 15.5kN, 16.2kN and 24.2kN for bracing variants 1 and variant 4 with 4.75mm and 6.0mm cables, respectively. This hierarchy will remain true for an assumed factor of safety in the design of anchor up to 2.5; beyond 2.5, the weakest component in the hierarchy for variant 1 and variant 4 with 4.75mm cable would be the brace assembly. It is thus important to consider the overstrength in the capacities of the brace assemblies, which is the difference between the rated and the actual capacities, during the design of anchors if anchor failure is to be avoided in cases where design force is exceeded.

It is essential to mention that there is uncertainty regarding the estimation of seismic demands, particularly due to the oversimplified procedures employed in the design standards. Therefore, some reasonable amount of safety again brittle failures is advisable even if the beyond-design actions are not considered a concern. Further, determination of the actual capacities of anchors is very challenging due to the influence of multiple variables on their strengths, such as the type of concrete and floor slabs. On the contrary, brace assemblies are tested for approval, and the acquisition of the test (actual) capacities is not similarly challenging, nor are such capacities dependent on the conditions of installation.

Another comparison is presented in Table 4 for the same piping system that considers the entire brace assembly of variant 1. The capacities of the components are based on test results and the anchor capacity corresponds to the presumed actual capacity (design capacity increased by an arbitrary factor of 1.5). The strength hierarchy in the brace assembly, inferred from the values reported in Table 4, reveals that the anchor will fail first if the design force is exceeded. To prevent the failure of anchor, the anchor capacity must exceed capacity of the PAC under tension, which is the weakest component in the hierarchy of the brace assembly. These comparisons serve as possible design scenarios and emphasize the need for application of capacity design principles to these elements. These results should not be generalized, as the hierarchy of strength, and the resulting failure mode in actual scenarios is dependent on so many variables, such as the actual capacity of the designed anchor. For example, the presumed actual capacity of the anchor equals 15.5kN if the arbitrary factor of safety is considered to be 2.5, in which case, the PAC under tension and the anchor have same capacities. To avoid using anchors with sizes that are considerably higher than that required to sustain the anticipated seismic demand, it is recommended to use brace assemblies (if there are options) whose rated capacities are not considerably higher than the anticipated demand; otherwise, the avoidance of anchor failure would require anchors that are much larger than that required by the actual demand to satisfy the desired strength hierarchy.

Table 4: Comparison of the capacities of variant 1 brace assembly and anchor.

Bracing	BAC		PAC		
	Avg. T (*kN*)	Avg. C (*kN*)	Avg. T (*kN*)	Avg. C (*kN*)	Anchor (*kN*)
Variant 1	23.8	25.3	15.5	24.5	9.2

CONCLUSIONS

1. A stable post-yield response was not observed in any specimen except to some extent in the PAC of variants 1 and 2 due to the elongation and/or opening of the pipe clamps. In all other cases, the deformation modes were such that a stable post-yield response could not have been formed. Simply put, the specimens failed in a brittle manner.

2. In all rigid bracing variants, failure was confined to the attachment components, except in the case of variant 3 (specimen with PACs), in which the brace element buckled under compression. This confirms the observation that brace elements are mostly stronger than the attachment components. These components will act as fuses if the demand exceeds the design force provided that the anchor failure does not precede. However, the tested specimens represent only one case with brace elements that were 500mm long. For brace assemblies with longer brace elements, buckling of the brace elements might be the weakest mechanism in the hierarchy as was the case with variant 3 under compression. For cable braces, the failure occurred in the cable with considerable deformation of the attachment components.

3. Utilizing the test results and data provided in the component catalogs by the manufacturers, it was shown through a design example that anchors can become vulnerable to failure if proper capacity design is not carried out. It is also important to note that bracing assemblies with brittle failures in the attachment components present the same consequences as the failure of an anchor. If ductile response is desired upon exceedance of design force, appropriate levels of ductility must be ensured in the attachment components.

RECOMMENDATIONS

1. A nominal ductility value of 1.25 is recommended for use in design for variants 1 and 2. This recommendation is based on the ability of components to deform, buckle, rotate, slip and twist, possibly resulting in reducing the instantaneous peak acceleration values.

2. Future research studies are recommended to study the behavior of such brace assemblies under static cyclic testing to better understand their failure modes and ductility capacities. Further, provision of information on failure modes and ductility capacity could be made mandatory for all manufacturers of brace assemblies as part of the approval or standardization process. This will facilitate design engineers in using a value of ductility that is appropriate for a chosen brace assembly.

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Appendix to

MONOTONIC TESTING OF BRACE ASSEMBLIES FOR PIPING SYSTEMS AND CONSIDERATIONS FOR CAPACITY DESIGN

Muhammad Rashid, Rajesh P. Dhakal and Timothy J. Sullivan

DATA SUMMARY

It can be observed in the force-deformation plots shown in the main article that the initial response was not ideally linear. This complicated the evaluation of the initial stiffness from the recorded response, and a procedure had to be chosen that could be consistently applied to all the specimens without over-idealizing the response in any case.

The initial stiffness was approximated by a straight line from the origin and passing through the ordinate at 0.7 times the maximum strength as shown in Figure A1 as representative cases of the method applied. The reported values of the ultimate displacement were calculated by evaluating the values corresponding to a drop in the maximum strength equal to 20%.

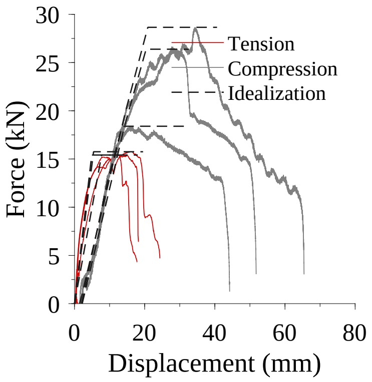
Tables A3 - A2 summarize different response parameters of the tested assemblies.

Table A1: Tensile strength of cable braces.

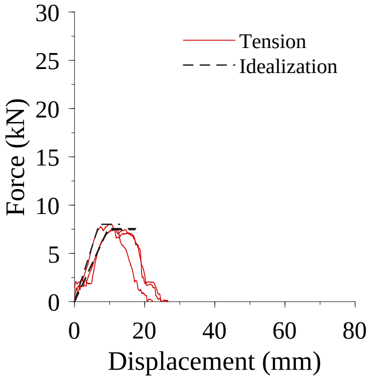
Specimen	Tension (*kN*)			
	1.	2.	3.	Avg.
2mm	3.4	3.3	3.4	3.4
3mm	7.0	6.5	6.9	6.8
4.75mm	15.2	17.8	15.7	16.2
6mm	24.4	24.1	24.2	24.2

Table A2: Failure displacement of cable braces.

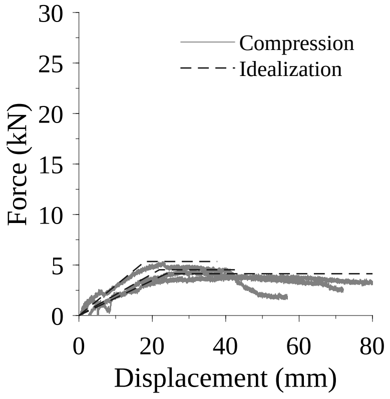
Specimen	Tension (*mm*)			
	1.	2.	3.	Avg.
2mm	15.1	14.9	15.0	15.0
3mm	28.9	24.6	24.2	25.9
4.75mm	26.7	20.9	24.9	24.2
6mm	35.0	37.0	35.3	35.8



(a) Variant 1 - PAC.



(b) Variant 2 - BAC.



(c) Variant 2 - PAC.

Figure A1: Idealization of experimental force-deformation responses for determination of yield point.

Table A3: Strengths of tested brace assemblies under tensile and compression loading.

Specimen	Tension (*kN*)				Compression (*kN*)			
	1.	2.	3.	Avg.	1.	2.	3.	Avg.
				Building-attachment components				
Variant 1	25.1	24.1	22.1	23.8	25.1	25.0	25.7	25.3
Variant 2	7.5	7.6	8.0	7.7	12.9	7.2	13.4	11.2
Variant 3	18.3	18.5	16.9	17.9	2.8[a]	5.6[a]	—[a]	4.2[a]
				Pipe-attachment components				
Variant 1	15.4	15.4	15.8	15.5	18.4	26.4	28.7	24.5
Variant 2	7.3	7.1	8.2	7.5	4.1	4.5	5.3	4.7
Variant 3	22.9	23.5	23.5	23.3	22.1	22.8	26.1	23.7

[a] Data not reliable; [b] data not available.

Table A4: Failure displacements of tested brace assemblies under tensile and compression loading.

Specimen	Tension (*mm*)				Compression (*mm*)			
	1.	2.	3.	Avg.	1.	2.	3.	Avg.
				Building-attachment components				
Variant 1	21.5	26.7	23.2	23.8	13.8	12.4	12.0	12.7
Variant 2	17.4	17.6	13.0	16.0	25.4	17.4	18.0	20.2
Variant 3	35.4	41.3	38.1	38.3	—[a]	—[a]	—[a]	—[a]
				Pipe-attachment components				
Variant 1	18.0	14.0	19.6	17.2	32.8	32.6	40.6	35.3
Variant 2	42.5	41.5	46.1	43.4	83.8	43.6	37.7	55.0
Variant 3	6.9	9.2	7.0	7.7	19.5	17.4	17.3	18.1

[a] Data not reliable.

Table A5: Initial stiffness of tested brace assemblies under tensile and compression loading.

Specimen	Tension (kN/mm)				Compression (kN/mm)			
	1.	2.	3.	Avg.	1.	2.	3.	Avg.
				Building-attachment components				
Variant 1	2.2	2.1	2.2	2.2	2.1	2.9	2.7	2.6
Variant 2	0.8	0.8	1.1	0.9	—[a]	0.8	—[a]	0.8
Variant 3	0.5	0.4	0.4	0.4	—[b]	—[b]	—[b]	—[b]
				Pipe-attachment components				
Variant 1	2.0	3.1	2.9	2.7	1.4	1.3	1.4	1.4
Variant 2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.2
Variant 3	3.9	2.8	3.8	3.5	2.0	1.7	2.2	2.0

[a] Response too non-linear to analyze; [b] data not reliable.