Determination of Component Ductility Factors for Seismic Design of Non-structural Elements

M. E. Kusz[1], M. Sfahani[2]

1. Corresponding Author. Principal Structural Engineer, Director, KUSCH Consulting Engineers, VIC 3699
   Email: martin@kuschgroup.com.au

2. Senior Structural Engineer, R&D Team Leader, KUSCH Consulting Engineers, QLD 4000
   Email: mimo@kuschgroup.com.au

Abstract

The design of seismic bracing for suspended mechanical, electrical, hydraulic and fire services within buildings has received increased attention within Australia in recent years. Many products and systems have been developed to brace suspended services against seismic loads that are determined in accordance with AS1170.4, the Australian Standard for seismic design actions. The calculation of seismic design loads includes ductility reduction factors that are not well understood and often misused by consultants and designers of seismic bracing systems. This paper critically reviews the principles behind ductility load reduction factors, and the conditions that must be present for these factors to be valid. The ductility levels that can be expected of typical suspended services and bracing systems are explored. The relatively low ductility of common seismic cable bracing systems is discussed, highlighting how common industry practice is resulting in the design and installation of seismic braces that are significantly undersized. Appropriate ductility factors are proposed for common suspended services and bracing systems, with consideration of the expected performance under ultimate and serviceability limit states.

Keywords: seismic design, building services, non-structural component, ductility factor, seismic bracing, performance-based solution.

1. Introduction

Australia has a low seismic classification, compared to neighbouring countries such as New Zealand and Japan, with the continental mainland located a significant distance from tectonic plate boundaries. Despite this fact, destructive and rare intraplate type earthquakes have occurred within the short-documented history of the country that necessitates engineered provisions for seismic risk mitigation. The Australian Standard AS1170.4 Earthquake Actions in Australia has been developed to ensure that earthquake loads are considered in the design of buildings in Australia, as a means of addressing such risks. Since the first release of this code in the early 1990s, it has been revised several times to improve seismic resilience in structural design. In 2007, Section 8 – Design of Parts and Components was added to AS1170.4, containing specific provisions for the seismic design of non-structural components, including building services. The provisions of this section are similar to those found within the International Building Code, with some modifications to suite to suite the Hazard Spectra and other parameters unique to AS1170.4. It is important to note that AS1170.4 is a design load standard only. While Section 8 specifies design loads for non-structural building elements, it provides no guidance on how to design such elements for these loads. Furthermore, it provides no guidance on acceptable performance levels of such elements, except to require that elements within an importance class 4 building must remain operational following a 1:500yr design event.

The standard provides three methods for the design of parts and components for earthquake actions, including the use of established principles of structural dynamics, the use of effective floor accelerations as described in Clause 8.2, or the simplified method as described in Clause 8.3. Clause 8.2 allows for the use of floor design accelerations, which would be determined by the building structural engineer during their seismic response analysis of the structure. Clause 8.3 provides a simplified, but more conservative approach, that approximates floor accelerations without any input from the structural engineer. While Clause 8.2 generally provides lower design loads, design floor accelerations are not commonly made available to non-structural trades, and therefore the simplified Clause 8.3 is more commonly used in industry.

The simplified Clause 8.3 method calculates the horizontal seismic load, F_c, used to design building parts and components, as the product of the following parameters

$$F_c = \left[k_p Z C_h(0)\right] a_x [I_c a_c / R_c]\, W_c \qquad 0.05\, W_c < F_c \leq 0.50\, W_c \tag{1}$$

where W_c is the component's weight and k_p, Z, $C_h(0)$, a_x, I_c, a_c, R_c are the probability, seismic hazard, spectral shape, height amplification, component importance, component amplification, and component ductility factors, respectively. These parameters are determined using AS1170.4. In Eq. (1), the product of the first three parameters, $k_p ZCh(0)$, denotes the site response and a_x is used to reflect the building response at a certain height. As such, F_c can simply be determined by reading the corresponding values from this standard and substituting in the above equation.

This paper investigates the component ductility factor R_c, which AS1170.4 specifies as R_c =1.0 for rigid components with non-ductile or brittle materials or connections, and R_c =2.5 for all other components and parts. No further guidance on the appropriate use of this ductility factor is provided in AS1170.4, or in the AS1170.4 Commentary. A ductility factor of R_c = 2.5 provides a 60% reduction in seismic design loads for parts and components and is therefore often desired from a cost perspective. Conversely, the incorrect use of this factor can result in parts and components being designed for loads that are only 40% of the actual required design load, and can result in significantly undersized outcomes that present unacceptable life-safety and performance risks.

The authors of this paper are aware of widely differing interpretations and practices within industry around the application of R_c. On the conservative end of the scale, R_c = 2.5 is used sparingly, and only for the design of structural members that will exhibit a good degree of ductile performance, and under ultimate limit-state (ULS) loads only. At the other end of the scale, R_c = 2.5 is being used frequently for design of whole systems, including elements with minimal ductility, steel and masonry connections, and with serviceability limit-state (SLS) loads for systems requiring continuous post-disaster functionality.

Urgent clarification on the appropriate use of R_c is required. In the following sections, the principles of ductility that underpin factors like R_c used will be investigated further.

2. Ductility factor or force-reduction factor? Does it matter?

Displacement or displacement ductility, commonly known as the ductility μ, has become a popular indicator to quantify structures' inelastic behaviour since initial attempts for development of performance-based structural design. Displacements are observable and can be realised publicly (visual), they are measurable with basic tools for real-world structures (residual), and they can easily be formulated for engineering application (mathematical). When it comes to force it is neither visual nor residual although it can be a mathematical indicator. Nevertheless, most structural design codes still cling to Force Based Design (FBD) methods because of appreciation of simple elastic analysis. A misleading concept herein is the equal displacement approximation which assumes that the elastic characteristics are the best indicator of inelastic performance. This simply implies that the force-reduction factor R is equal to displacement ductility μ, i.e. $R=\mu$, as shown in Figure 1.

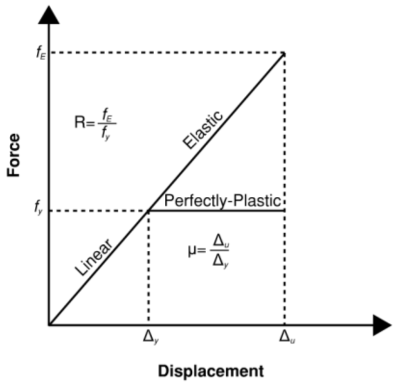


Figure 1 Equal displacement approximation

So far, it can be noted that AS1170.4 also utilises the above principle to specify R_c, as in the simplified method. There have been problems with this approach, 'in that it has long been confirmed that the equal displacement approximation is inappropriate for both very short and very long period structures, and is also of doubtful validity for medium period structures when the hysteretic character of the inelastic system deviates significantly from elastoplastic' (Priestly, 2000).

In general, the design displacement (seismic demand), i.e. Δ_d, can be expressed as

$$\Delta_d = \Delta_y + \Delta_p \leq \Delta_c \quad (2)$$

where Δ_y and Δ_p are displacement at first yield and plastic deformation, respectively, and Δ_c is capacity displacement (seismic limit-state). To use the ductility ratio AS1170.4 specifies for nonductile components, i.e. 2.5, Δ_p must be larger than 1.5 Δ_y. The reason is hysteretic energy dissipated within the nonlinear responses (e.g. $f_y \Delta_p$ for the perfectly-plastic case in Figure 1) increases damping and thus the seismic demand decreases. Note that Δ_c can also be expressed by different ductility ratios of Δ_y, to address different performance limit-states. These ductility ratios specify the seismic capacity and are different from the AS1170.4 specifications for seismic demand. When the limit-state ductility ratio (i.e. seismic capacity) is less than one (i.e. yielding threshold), Δ_d cannot be reduced since no energy dissipation occurs.

In contrast, interpretation of the above explanation with the force-reduction factor holds

$$F_c = f_y + f_E \le F_u \tag{3}$$

where F_c is the component force in Eq (1), f_y is the yielding force, and F_u is the ultimate limit-state load capacity (i.e. the nominal load capacity reduced by a factor of safety). For steel structures, the Australian Standard AS4100 (1998) applies nominal load capacities lower than the plastic section bending moment or force, f_p. As such, f_E is by no means bigger than f_p however, with the assumption of equal displacement approximation, f_E must be bigger than 1.5 f_y for nonrigid components as per AS1170.4 specifications. This raises the question if adequate ductile performance can then be achieved for different seismic bracings. Such requirements are scrutinised for common seismic bracings, in the next section.

3. Ductility of suspended building services

Typical buildings contain a wide variety of suspended, non-structural systems and services, including ceilings, electrical, hydraulic, HVAC and fire services. These elements are typically suspended from the overhead building structure via steel threaded rod or plain rod (ceilings). While these 'suspended rods' provide suitable structural support for vertical gravity loads, they typically provide very little horizontal load resistance. Therefore, in order to resist horizontal seismic loads, suspended building elements typically require the addition of lateral load resisting systems at regular intervals. Often referred to as 'seismic braces', common systems include seismic cable braces, rigid braces using cold-formed steel (CFS) strut or threaded rod, or cantilevered steel post braces, which are discussed in further detail below. Each bracing system includes connections to the building structure and connections to the suspended service, and provides the inertial loads of the suspended service a load path back to the building structure.

When seismic design loads are determined for these bracing systems, it is essential that the ductility factor selected is appropriate for all elements within the system. As different elements within a brace will have different degrees of ductility, the design of a seismic design will inevitably result in different design loads for each element.

3.1. Threaded rods

For relatively load seismic loads, or when services are installed in close proximity to the building structure, threaded-rod support systems do provide some lateral resistance which can be relied upon. Figure 2 shows the load-displacement graph for a Grade 4.6 threaded rod under nonlinear static push-over (SPO) analysis. Both vertical (load) and horizontal (displacement) axes were normalised by the theoretical yielding values for parametric justification purposes. As seen, the first yield happens at μ=1.0 and R=1.0. The plastic section capacity (in terms of bending moment or force, f_p) can be also determined theoretically for circular cross section, i.e. 1.7 f_y. This is approximated to be at μ=2.2 and R=1.7, from the pushover curve in Figure 2. Finally, the steel hardening process can be determined by tracing the slope of the SPO curve, i.e. where the decreasing rate of change of slope becomes constant. This threshold is approximated to be at the μ=3.3 and R=1.82. It should be noted, a quasi-dynamic (cyclic) test which captures the degrading Bauschinger effects could result in slightly varying numbers.

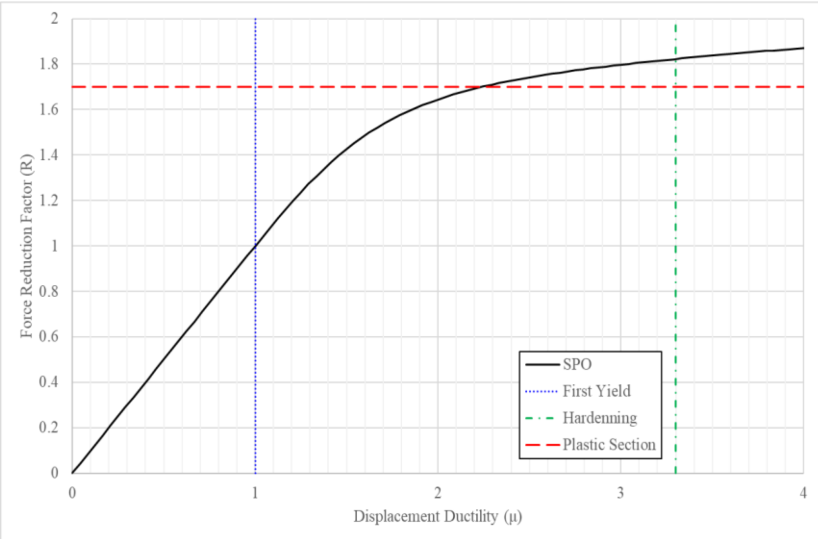


Figure 2 Inelastic response of thread rods gravity hangers

For the displacement-based design (DBD), the area under the SPO curve (i.e. work equals to force times displacement) can be interpreted as the dissipated hysteresis energy during inelastic behaviour. This increases the initial damping of the dynamic system, to a higher equivalent damping, which would diminish the cyclic responses. In other words, as a consequence of this process, the inelastic dynamic responses are less than static ones. There are some relations to establish such equivalent damping ratios (Priestly, 2000, Filiatrault et al., 2018) based on the originally proposed equation by Jacobsen (1960):

$$\xi_{eq} = \frac{E_{\Delta}}{2\pi k_{eq} \Delta^2} + \xi_i \tag{4}$$

where E_{Δ} and k_{eq} are the energy dissipated per cycle from the hysteretic behaviour and the equivalent (secant) inelastic stiffness at the target displacement Δ, respectively, and ξ_i is the nominal inherent damping ratio. Considering ξ_i = 5% for a non-structural component suspended by threaded rods, the equivalent damping, based on Eq (4) and the SPO analysis in Figure 2, is ξ_{eq} = 32%. The displacement seismic demand corresponding to the equivalent viscous damping can be obtained through empirical modification factors or codified, as shown in the relationship below (CEN, 2004):

$$S_{D,i} = S_{D,eq}\sqrt{\frac{0.10}{0.05+\xi_{eq}}} \tag{5}$$

Subsequently, for performing a linear static analysis, the total seismic demand can be reduced by about 48% (i.e. dividing by a factor of 1.92).

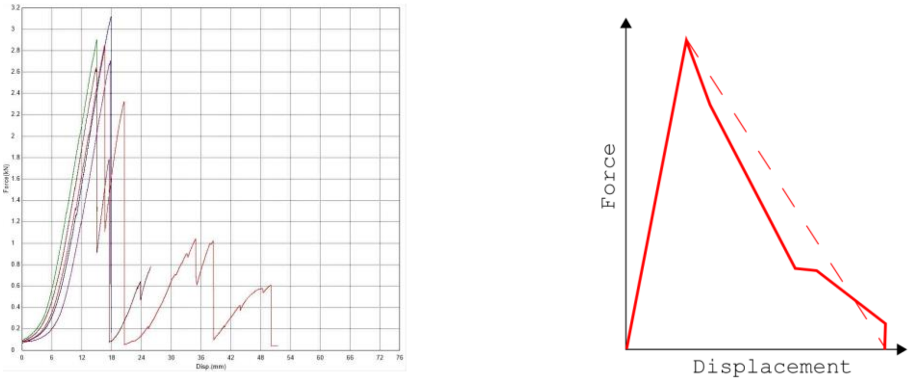
In an FBD, a primary question is the effect of ductile performance in the vertical load axis, similarly to that which can be observed in the horizontal displacement axis. As seen in Figure 2, this ductile performance in the vertical axis can't be achieved and it discourages using R_c = 2.5, as AS1170.4 advises for nonductile components can be expected. In fact, the *Rc* factor is applied here as substitute for the process explained above. However, to be comparable to that process, a R_c = 2.5 implements a ξ_{eq} = 57% or ξ_i = 30% requirement. Expecting such or higher damping factors for all non-structural components which are commonly classified as nonrigid is not realistic. In addition to this fact, the deterministic approach within AS1170.4, for choosing R_c = 2.5, misleads engineers without enough experience in seismic design. In the following section, the ductility of seismic bracing solutions commonly in use within the Australian building services industry are scrutinised.

3.2. Cable bracing

Seismic cable bracing is a common, versatile method for seismic bracing of suspended non-structural components. Their ideal uniaxial load performance, simplicity of installation and cost-efficiency makes them an appealing solution in many applications. Figure 3 shows some common brace configurations for suspended building services.

Figure 3 Cable braces used to seismically restrain building services

Destructive load testing of seismic cable bracing has demonstrated that these systems show negligible ductility after yielding and before reaching their nominal breaking capacity. For example, see Figure 4(a) which shows the load-displacement responses of such cable systems. As seen, the graph starts with a very low initial slope which corresponds to the take-up of play within looped cable connections. The load and displacement increase linearly to a peak, but there is no ductile behaviour after this point. The next sudden drop and increasing behaviour, which is observed repeatedly, is due to snapping of individual wires within the cable, starting from the most exterior fibres.



(a) Static testing (b) Schematic

Figure 4 Force-Displacement response of a cable seismic bracing

Note the response illustrated in Figure 4(a) was recorded during a static tensile test. Therefore, under a cyclic loading regime, one or more wires would fail (breaking) in each load cycle while the remaining wires remain linear elastic. This makes the overall load-displacement response of the cable bracing triangular, as shown schematically in Figure 4(b). No softening-hardening behaviour can be seen in this response. In addition, the fact that wires are either elastic or snapped discourages consideration of any energy dissipation during the degrading response (dashed line). These observations imply that, despite using steel construction, this seismic cable bracing exhibits non-ductile behaviour and should be designed with R_c =1.0.

3.3. Diagonal struts

Cold-formed steel (CFS) channel or 'strut' is widely used in many different configurations to support building services and non-structural components. Figure 5 shows an example of struts used to seismically restrain hydraulic services. These braces are mainly fabricated to provide seismic resistance via their axial stiffness (tension and compression), but they are also used as a two-point hinge brace (longitudinal and lateral), i.e. like a simply supported beam, or less effectively as a cantilevered beam. The CFS struts' material properties are similar to that of threaded rods. In addition, the slotted fabrication and/or thin-walled open cross-sectional properties of the struts, which trigger the necking and/or local distortions, promise a fairly ductile behaviour. This also applies to the baseplates and shear/tension bolts that are used in conjunction with the struts. However, such ductile behaviour is not guaranteed when friction resistance operated fittings such as channel nuts are used with struts. This is evidently because no extra load capacity can be expected when the friction load capacity is reached. Therefore, as a matter of load reduction for the design purposes, R_c = 1.0 must be used to design the friction resistant fittings but the rest of assembly can be designed with R_c = 2.5.

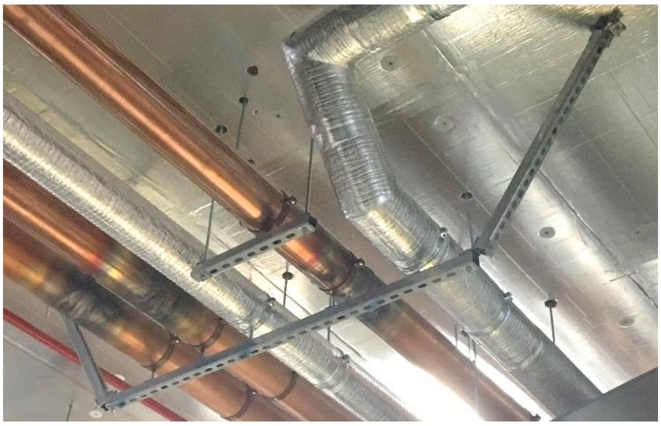


Figure 5 Diagonal CFS strut bracing

3.4. Cantilevered post

The single or multi-point cantilevered seismic posts are fabricated using a robust CFS strut or square hollow section (SHS) welded or bolted to a square baseplate, which provide resistance in all directions through their bending moment capacity. Figure 6 shows examples of cantilever strut post bracing. Due to the lower rotational (than axial) stiffness, which produces such capacity, expecting a ductile behaviour for a seismic post before absolute failure is fair and therefore using R_c = 2.5 is appropriate. Nevertheless, special attention needs to be paid to some welding or bolted connections (post to baseplate) types to ensure they are not brittle (e.g. poor welding or some Grade 8.6 or stainless-steel type bolted connections).

Figure 6 Cantilevered post bracing

3.5. Concrete anchors

Seismic rated concrete anchors are a fundamental element of seismic bracing. In general, any type of seismic bracing needs to be restrained via such anchors, to comply with the Australian Standard AS5216 (2018). The design process explained in this standard has yet not been validated for seismic loads and users can apply the European Standard EN 1992-4 (2018) for such purposes. Nevertheless, the extensive diversity of these anchor products and the tedious design process in these standards has led most manufacturers to develop their specific design software and technical support for the industry.

Concrete anchors are manufactured from steel and metal alloys with various material properties and they are designed to work in tension and shear. For most cases, the existing design software considers the initial combined yielding stress as the anchors’ failure threshold. In addition, the concrete cone or edge failure is a likely mechanism in seismic anchors. As a consequence of such a complex behaviour, justification for ductile performance becomes very difficult and all anchors are recommended to be designed with R_c =1.0.

4. Conclusion

The seismic design of non-structural components and building services is a relatively new concern within Australian building construction. The Australian Standard AS1170.4 provides the seismic design loads for such services, but minimal guidance on how to design such systems for these loads. In this paper, the principles of load reduction factor, R_c (i.e. the so-called component ductility factor in AS1170.4) have critically been discussed and reviewed. For engineers involved with the seismic design of building services, it is important to understand that a ductility factor of $R_c = 2.5$ will reduce the seismic design load of a seismic brace or support, to utilise the plastic performance of that brace or support. Appropriate consideration should therefore be given to the suitability of bracing systems operating beyond their yield limit, if large ductility factors are to be used. The following recommendations for seismic design are made:

- Displacement is a more appropriate indicator of structural performance than force due to it being observable, measurable and applicable for design and analysis purposes. The validity of equal displacement approximation is doubtful, specifically when systems are designed to exhibit inelastic behaviour and for the ultimate limit-state.

- For DBD method at $\mu = 3.3$, threaded rods approximately show an extra 27% damping ratio ($\xi_i = 5\%$ and $\xi_{eq} = 32\%$) due to hysteresis energy dissipation which reduces the seismic demand by approximately 48%. Using $R_c = 2.5$ in a FBD leads to a 60% load reduction and effectively implements a $\xi_{eq} = 57\%$ or $\xi_i = 30\%$ requirement.

- Seismic cable brace systems do not perform in a ductile manner and must be designed for loads determined using $R_c = 1.0$. The use of $R_c = 2.5$ will result in design loads that are only 40% of the required demand. With break strengths of approximately 1.5 to 1.7 times typical published ULS capacities, cable systems designed to their capacity with $R_c = 2.5$ would be expected to fail under a seismic design event.

- Diagonal or horizontal struts made of CFS are relatively ductile seismic bracing systems and can be designed with $R_c = 2.5$, unless friction resistance operated fittings are used with the struts in which case seismic design must be conducted by using $R_c = 1.0$.

- Cantilevered posts with welded (or bolted) baseplates are also ductile seismic bracing systems and can be designed with $R_c = 2.5$. Special attention however needs to be paid to ensure the same level of ductility is present for the welded or high strength metal bolted connections in tension and shear.

- Seismic rated concrete anchors have a brittle failure mechanism and do not exhibit ductile behaviour. Anchors should always be designed with $R_c = 1.0$.

- While R_c = 2.5 may be appropriate for ductile brace systems under ULS loads, they are unlikely to be appropriate for SLS2 loads where post-disaster functionality is required. In most cases, 1:500yr loads with R_c = 1.0 will exceed 1:1500 loads with R_c = 2.5 and will likely govern the design.

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