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DESIGN PROCEDURE FOR DUCTILE TENSION-ONLY SEISMIC BRACING WITH AN ENERGY DISSIPATION RING

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ABSTRACT: This paper will present a design solution for a ductile, tension–only seismic bracing with the use of an energy dissipating ring. This type of bracing behaves very well under seismic loading and has shown, by testing carried out in conjunction with the University of British Columbia, that it can reach very high post elastic drift limits. The presented procedure is a method created by the author and is based on information collected during the research testing program performed by the Civil Engineering Department at the University of British Columbia. The team was led by Professor Carlos Ventura, in collaboration with Dejan Erdevicki from Erdevicki Structural Engineering.

The presented design procedure describes the behaviour of the system, the relation between energy, forces, drift limits and capacities of the ring. It also includes geometrical limitations and requirements for the ring element and bracing system, to ensure that target drifts can be achieved.

It allows the user to calculate seismic forces and reduction factors based on an energy criterion and the chosen final drift of the structure. For longer period structures, an equal displacement principle was discussed and considered.

The procedure can be used for seismic capacity design and is easily adjusted to suit applicable national codes. Ring capacity tables and examples are also included.

This ductile, tension–only bracing, with an energy dissipating ring, can be used for new structures, as well as for the retrofit of existing ones. The system is relatively simple and allows for easy replacement of the ring after an earthquake event if needed. The application of the bracing system for buildings, including multi-storey structures, will be discussed.

1. Introduction

The tension–only bracing illustrated in Fig. 1 is a simple and ductile bracing system that can be used as a seismic load-resisting structural element. The design procedure presented in this paper is a conservative method created by the author, based on the information collected during a series of tests on a full-scale braced frame carried out at the University of British Columbia. The testing program included quasi-static, cyclic and shake-table tests. Work on this research project started 2007 and most of the tests were performed from 2011 to 2013. The test program was performed at the UBC Earthquake Engineering Laboratory by a research team led by Professor Carlos Ventura, in collaboration with Dejan Erdevicki from Erdevicki Structural Engineering.

The test program was limited to 45 degree diagonals and one-story bracing. The author is confident that the procedure can be used also for multi-story bracing systems. The optimal angle for diagonals is 45°. Until further test results are conducted, the author recommends restricting the angle of diagonal bracing α to between 40° and 50°.

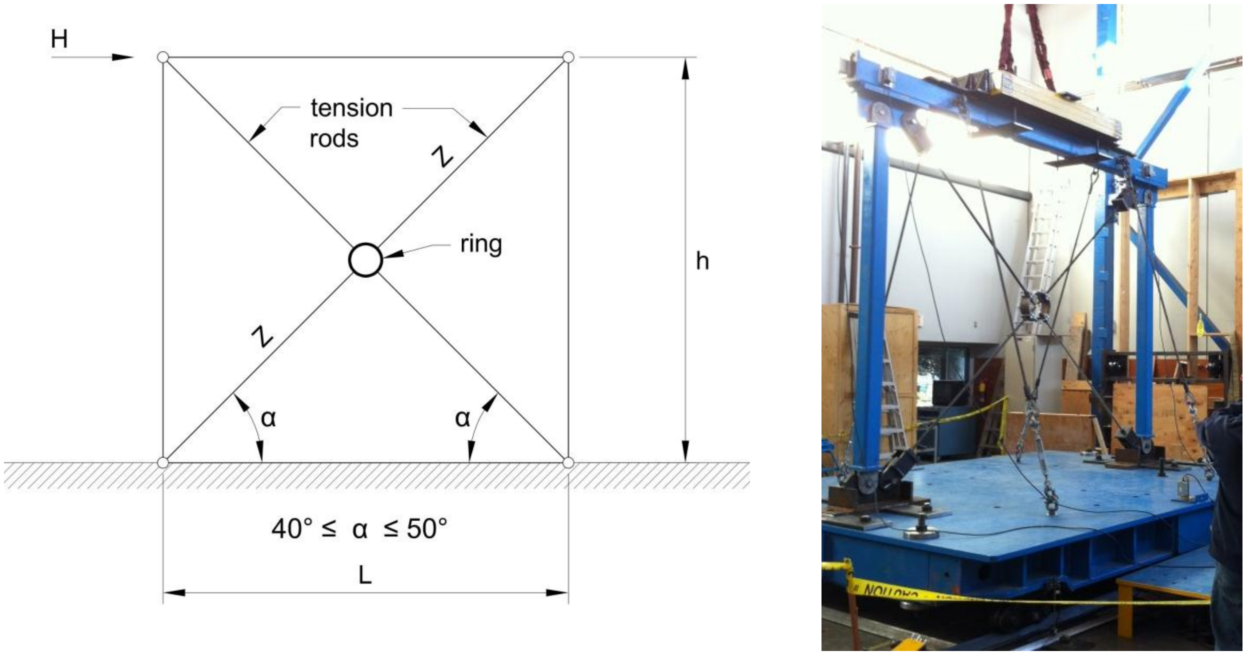

Fig. 1 – Bracing System

The system will dissipate energy by forming plastic hinges inside the central ring. Control of the number of hinging points and their locations is achieved using clamp plates. The design procedure presented in this paper is valid only if all the requirements for the ring and system design described below are fulfilled.

2. Notation

Table 1 – Terminology.

Abbreviation	Definition
A	length of clamp plates, mm
A_{eq}	effective rod cross sectional area, mm^2
A_r	rod cross sectional area, mm^2
B	width of ring, mm
C	dimension between clamp plates, mm
D_{eq}	equivalent diameter of rod, mm
D_i	internal diameter of ring, mm
D_o	external diameter of ring, mm
E	modulus of elasticity of steel, MPa
F_u	tensile strength of ring material, MPa
F_y	yield strength of ring material, MPa
H	horizontal force, kN
H_{el}	elastic seismic horizontal force, kN
H_{ov}	overstrength horizontal force, kN
H_y	horizontal force causing yield, kN
h	height of braced frame, mm
h_i	height of i^{th} floor in multi-storey frame, mm
K	initial elastic stiffness of bracing, kN/mm
K_r	elastic stiffness of ring, N/mm
L_d	length of diagonal, mm
M_f	factored bending moment at a section, kNmm

Abbreviation	Definition
$M_{f\ wind}$	factored bending moment for wind at a section, kNmm
M_r	seismic flexural resistance at a section, kNmm
M_{rw}	factored flexural resistance for wind at a section, kNmm
R_0	material factor as specified in the applicable design code
R_d	ductility factor as described in Section 6
T_1	first natural period of vibration, sec
t_r	thickness of ring, mm
t_w	clamp plate thickness, mm
X, Y	sections of peak ring flexure
Z	diagonal force, kN
Z_{el}	elastic seismic rod tension force, kN
Z_f	factored rod tension force, kN
$Z_{f\ wind}$	factored rod wind force, kN
Z_r	ring factored tension resistance, kN
$Z_{r\ wind}$	ring factored tension wind resistance, kN
Z_y	ring yield tension capacity, kN
δ	horizontal deformation corresponding to H
δ_{el}	elastic horizontal deformation
δ_{max}	maximum horizontal deformation
δ_y	horizontal deformation causing yield
Φ	hole diameter, mm

3. Ring General Requirements

The ring and washers are generally as shown in Fig. 2.

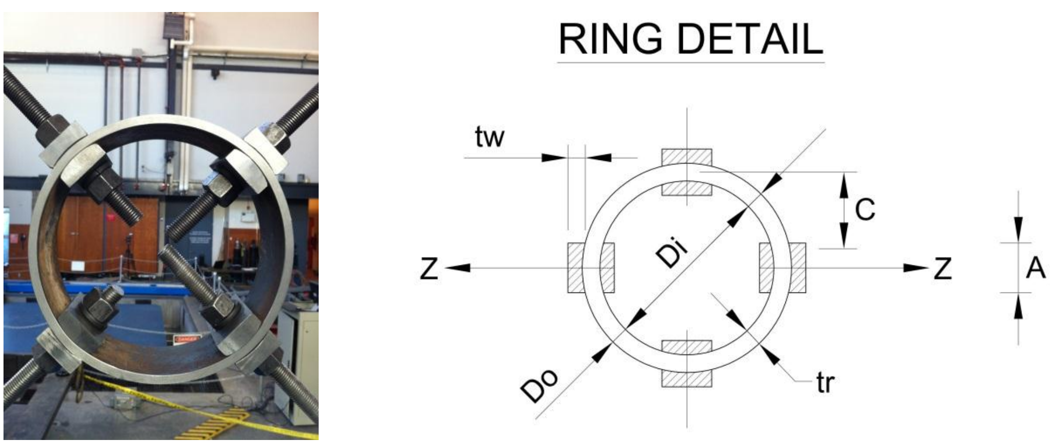

Fig. 2 – Ring Geometry

Based on current testing following geometric requirements are suggested:

- D_i > 142 > h / 21
- $t_r \geq 7$
- B > 90 > 4 * Φ

The minimum tested inside ring diameter Di was 149 mm for a frame height of 3160 mm (h / Di = 21.2). Larger rings performed better as the post-elastic frame deformation for all quasi-static tests was limited to the same drift of 0.015 * h. For that reason it is suggested that Di > h / 21 and Di > 142 mm. All tested rings were 90 mm wide and had 22 mm holes (B / Φ = 4.1). The suggested B / Φ ratio is to limit the ring net-section reduction.

When tested, rings without double clamp plates fractured at the hole locations, whereas rings with double clamp plates fractured at the edges of the clamp plates and performed much better in the tests. All tested clamp plates were 50 mm long, 19 mm thick and had 22 mm diameter holes. These clamp plates worked well for overstrength diagonal loading of about 110 kN.

Making the clamp plates too narrow or too thin will reduce the clamp plate capacity and would impair ring performance. The clamp plates should remain elastic in resisting overstrength loading and should be capable of distributing the load evenly across the width of the ring. In addition, the clamp plates should not be too long in order to maximize the post-elastic deformation capacity of the rings. The minimum Di / A ratio tested was 2.98. The proposed Di / A ratio are therefore >3.0.

The following geometric limits are proposed, but could be varied in the light of satisfactory test results:

- *A ≤ Di / 3, ≥ 50, ≥ 2 * rod diameter, ≥ Do / 6*
- *tw > 19, > B / 5, > 0.4 * A, > 1.25 * tr*

- Clamp plate radius to match inside and outside ring radius.
- Clamp plate corners to be chamfered 2-3 mm.
- Clamp plate material to be as strong, or stronger than the ring material.
- Ring and clamp plate holes are to be 2 mm larger than the rod diameter.
- Rod nuts and lock washers to be placed on the inside and outside of the ring.

Fig. 3 – Ring Without Double Clamp Plates

Fig. 4 – Ring With Double Clamp Plates

4. Ring Capacity, Factored Loading and Overstrength Factor

The following simplified relationship between the rod tension force and ring moments can be used:

$M_f = 0.3 * Z_f * C$ or $Z_f = M_f / (0.3 * C)$

where $C = (D_o - t_r) / 2 - A / 2 + 5$ mm

Numerical modeling of the ring and clamp plates would be another way to determine the maximum moment at Section X.

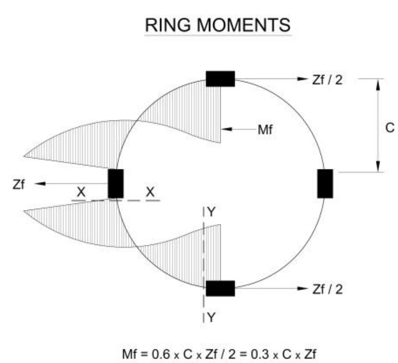

Fig. 5 – Ring Moments

4.1. Non-Seismic Loading

For non-seismic loading, the ring bending resistance at Section X should be calculated based on the applicable steel design code, using the gross section B * tr without reduction for the hole. The suggested ULS stress limit is 0.9 * Fy.

The capacity check at Section Y is not critical, as the section tension capacity is significantly larger than the corresponding moment capacity, and the initial moment at Section Y is only about 67% of the corresponding moment at Section X.

4.2. Seismic Loading Combinations

For seismic design, the following ring resistance can be used:

$\mathbf{M_r = M_y = 1 / 6 * F_y * B * t_r^2}$ and $\mathbf{Z_r = Z_y = M_r / (0.3 * C) = 1/6 * F_y * B * t_r^2 / (0.3 * C)}$

The seismic design requirement will be:

$\mathbf{M_r \geq M_f}$ **<u>or</u>** $\mathbf{Z_r \geq Z_f}$

M_f can be calculated using the design factored tension rod force $Z_f = Z_{el} / (R_d * R_0)$.

Z_{el} = elastic diagonal ULS seismic force corresponding to H_{el} calculated using the applicable building code.

1.0 ≤ Ro ≤ 1.5, Ro = 1.5 is recommended.

The overstrength ring capacity will exceed the tensile strength of the material, Fu and the ring will gain significant post-elastic capacity through shape change. Based on experimental results, the maximum ring overstrength could be between 2.0 and 2.5. The author suggests using an overstrength factor of 2.5 for design of all connections, tension rods, and affected structural bracing elements and foundations. The overstrength factor for rings larger than 210 mm could be reduced to 2.0.

4.3. Example and Capacity Table

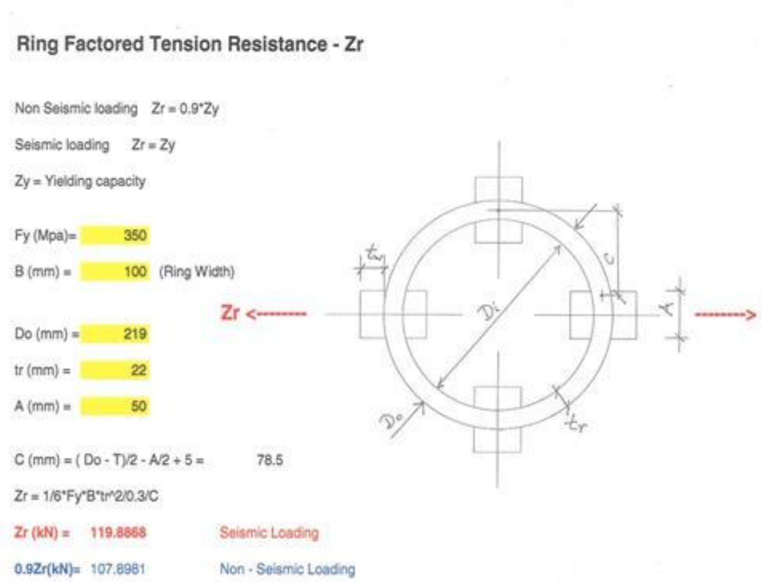

Fig. 6 – Ring Capacity Example

Capacity Table

Ring	Do (mm)	tr (mm)	B (mm)	Fy (Mpa)	A (mm)	**Zr (kN)** - Seismic Capacity
168/8	168	8	100	350	50	**21**
168/9.5	168	9.5	100	350	50	**30**
168/11	168	11	100	350	50	**40**
168/13	168	12.7	100	350	50	**54.5**
219/8	219	8	100	350	50	**14.5**
219/9.5	219	9.5	100	350	50	**20.5**
219/11	219	11	100	350	50	**28**
219/13	219	12.7	100	350	50	**37.5**
219/16	219	16	100	350	50	**61**
219/22	219	22	100	350	50	**120**
219/25	219	25.4	100	350	50	**163**
273/8	273	8	100	350	60	**11.5**
273/9.5	273	9.5	100	350	60	**16.5**
273/11	273	11	100	350	60	**22**
273/13	273	12.7	100	350	60	**30**
273/16	273	16	100	350	60	**48**
273/22	273	22	100	350	60	**94**
273/25	273	25.4	100	350	60	**127**
324/11	324	11	100	350	60	**18**
324/13	324	12.7	100	350	60	**24**
324/16	324	16	100	350	60	**38.5**
324/22	324	22	100	350	60	**75**
324/25	324	25.4	100	350	60	**101**
356/13	356	12.7	100	350	75	**22.5**
356/16	356	16	100	350	75	**36**
356/22	356	22	100	350	75	**70**
356/25	356	25.4	100	350	75	**94.5**
406/13	406	12.7	100	350	75	**19**
406/16	406	16	100	350	75	**30.5**
406/22	406	22	100	350	75	**59**
406/25	406	25.4	100	350	75	**79.5**

Table T1

Fig. 7 – Ring Capacity Table

5. Bracing Stiffness

The initial elastic bracing stiffness K = H / δ.

The bracing stiffness is important in estimating the ductility factor Rd and should therefore be carefully determined. The bracing should be modeled with one diagonal only and should include the ring.

Alternatively, the ring stiffness Kr from Table T2 can be used to calculate the required effective diagonal cross sectional area Aeq and to model only the diagonal without the ring using Aeq.

$$\mathbf{A_{eq} = A_r * L_d / (A_r * E / K_r + L_d - D_o)}$$

Example:

L_d = 4500 mm

A_r = 380 mm^2 (for 22 mm diameter rod)

Ring size: 324/25.4

K_r = 55 kN/mm (from Table T2) = 55 000 N/mm

E = 210 000 MPa

Required equivalent diagonal cross section:

Aeq = 380 * 4500 / (380 * 210000 / 55000 + 4500 - 324)

Aeq = 303 mm^2

Or, equivalent rod diameter Deq = 19.7 mm.

The bracing should be modeled with one diagonal rod using an equivalent rod diameter of 19.7 mm.

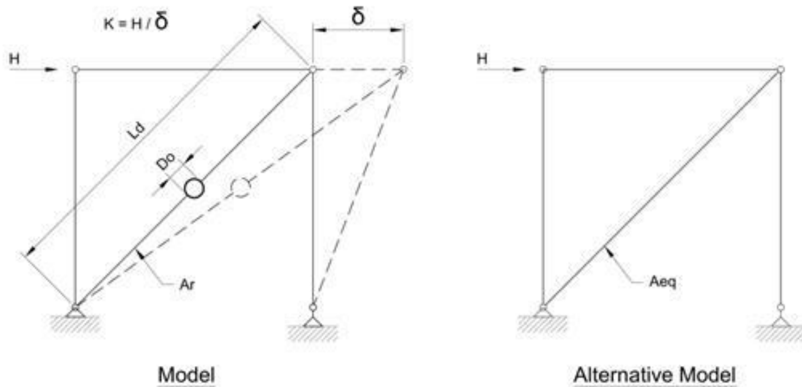

Fig. 8 – Bracing Stiffness Models

Ring Stiffness Table

Ring	Do (mm)	tr (mm)	B(mm)	**Kr (kN/mm)**
168/9.5	168	9.5	100	20
168/13	168	12.7	100	50
219/13	219	12.7	100	24
219/22	219	22	100	120
273/13	273	12.7	100	12
273/25	273	25.4	100	95
324/13	324	12.7	100	6.8
324/25	324	25.4	100	55

Table T2

Fig. 9 – Ring Stiffness Table

The ring stiffness Kr for thicknesses not listed in Table T2 could be estimated using a ring of the same diameter and adjusting the stiffness using the tr^3 ratio.

Example:

For the 219/16 ring, a thinner ring with the same diameter, 219/13 will be used. For the 219/13 ring, from Table T2, Kr = 24 kN/mm. Therefore, for the 273/16 ring, $Kr = 24 * 16^3 / 13^3 = 44.7$ kN/mm.

If the designer wishes to increase the bracing stiffness or capacity, it can be done by increasing the rod diameter, or by using multiple rods as shown in Fig. 10, in which case the ring should satisfy the geometric requirements described in Section 3.

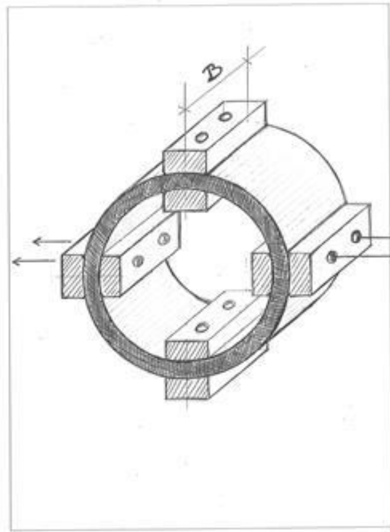

Fig. 10 – Ring with Multiple Rods

6. Energy and RD

6.1. Systems with the First Period of Oscillation T1 < 0.5(s)

An energy criterion will be used to establish the ductility factor Rd as shown in Fig. 11. Test results have verified that diagonal tension-only bracing with a central ring can reach a post-elastic drift limit of at least 1.5 %. In addition, it was also evident that the system overstrength factor is higher than the Fu / Fy ratio. The overstrength area ΔE1 is larger than the area ΔE2 for δy < 0.0075 h, and is used to compensate for the ΔE2 area, and allow for simplification of the formula for E1 shown in Fig. 11.

As a result: **Rd = 2 * K * δmax / Hel (Eq 6.1)**

Substituting Hel / δel for K: **Rd = 2 * δmax / δel (Eq 6.2)**

Hel = The elastic seismic force calculated using the applicable building code

δel = elastic force displacement

δmax = 0.015 * h = maximum displacement limit

Suggested Rd Limits:

2.0 ≤ Rd ≤ 5.0

It is important to note that the Rd factor can be increased using higher stiffness K, and will be reduced for a higher elastic force.

Example:

- H_{el} = 100 kN
- K = 5 kN/mm
- h = 3000 mm
- δ_{max} = 0.015 * 3000 = 45 mm
- R_d = 2 * 5 * 45 / 100 = 4.5
- Or using $R_d = 2 * \delta_{max} / \delta_{el}$
- δ_{el} = 20 mm
- R_d = 2 * 45 / 20 = 4.5

Therefore, if the system is properly modelled and the elastic seismic forces are applied, the factor R_d is the ratio between the maximum chosen displacement and the elastic displacement.

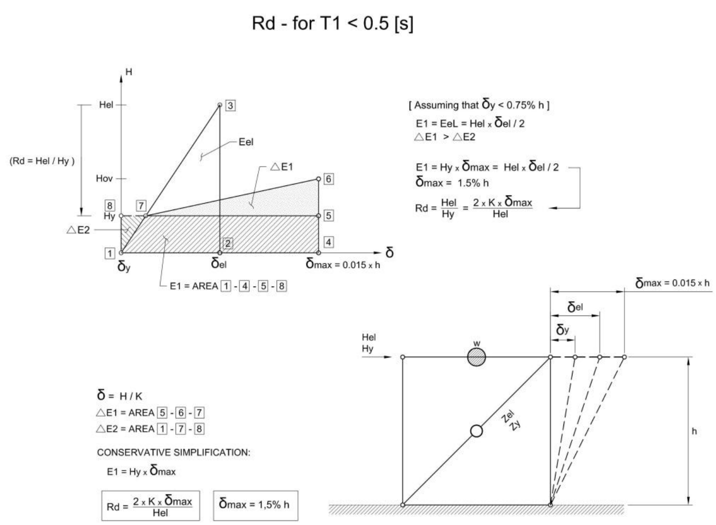

Fig. 11 – Energy and Drift Diagrams

6.2. Systems with a First Period of Oscillation T_1 >0.5(s)

The generally accepted the equal displacement principle shown in Fig. 12 can be used as an alternative to the previously described approach. Further testing will be required to verify that the equal displacement principle is adequate and to establish a realistic limit to the force reduction factor.

An important limitation of the system in this case is that the elastic force displacement δel must be <0.015 * h. If the designer decides to use the equal displacement approach, the author suggests limiting the force reduction factor Rd to 5.0.

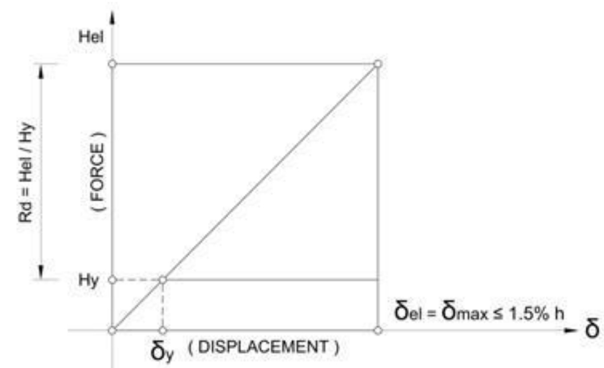

Fig.12 – Equal Displacement Principle Diagram

6.3. Multi-Storey Systems

The force reduction factor, Rd can be checked at each storey level using the elastic seismic shear force at that level and corresponding K and δmax = 0.015 * hi at that level. Rd can also be determined by calculating the elastic displacements at each level and using Equation 6.2. See Fig. 13 for more details.

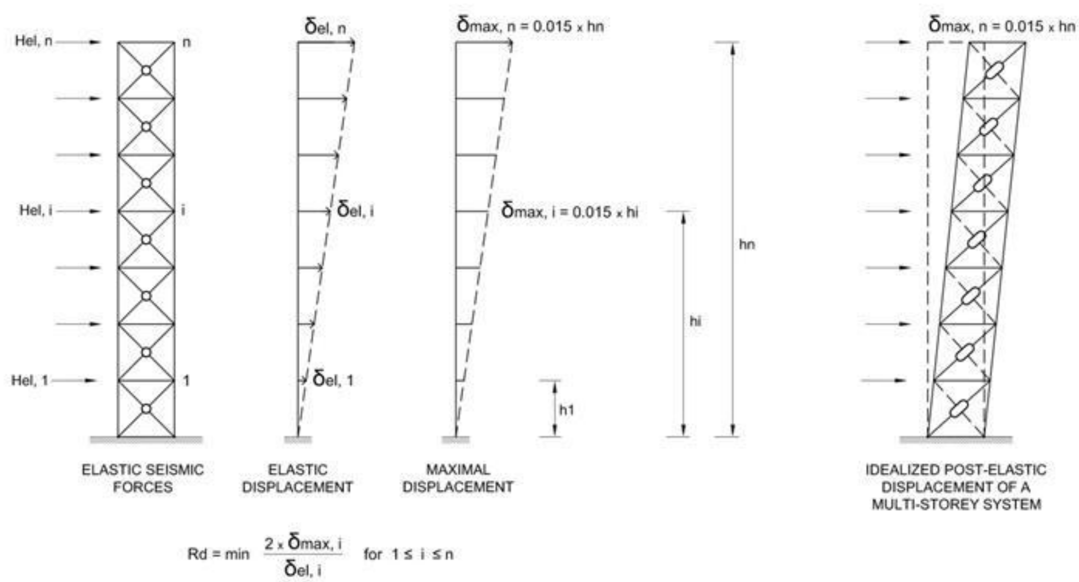

Fig. 13 – Multi-Storey Systems

Ring ductility should be used at each floor level and should be designed with respect to design seismic shear force at that level. Further research should be undertaken on the behaviours of the multi-storey system to ensure that the plastic behaviour is not concentrated at the lower storey, but is distributed throughout.

7. Design Procedure for Systems with T1 < 0.5 s

- Design the ring and bracing for non-seismic loading.

- Calculate the first period T1, and system stiffness, K.
- Calculate the elastic seismic force Hel based on the applicable design code.
- Calculate Rd as described in Section 6.
- Calculate the seismic design force Hf = Hel / (Rd * R0).
- Calculate the corresponding diagonal force Zf.
- Design the ring as described in Section 4.
- Check the stiffness K based on the chosen ring size, and if K is lower than initially assumed, repeat the above procedure. If the chosen ring is stiffer than initially assumed, the system is safe in the case that it does not affect the force Hel. The designer can elect to refine the design or not.
- Design tension rods, connections and all affected bracing and foundation elements for overstrength forces Hov = 2.5 * Hy (2.0 * Hy for rings > 210 diameter) but Hov < Hel / R0.

8. Design Procedure for Systems with T1>0.5 (s) using Equal Displacement Principle

- Design the ring and bracing for non-seismic loading.
- Calculate the first period T1 and system Stiffness K.
- Calculate the elastic seismic force Hel based on the applicable design code.
- Assume Rd = 5.
- Calculate the seismic design force Hf = Hel / (Rd * R0).
- Calculate the corresponding diagonal force Zf.
- Design the ring as described in Section 4.
- Check T1 and K based on the chosen ring size.
- K must be larger than Kmin = Hel / δmax.
- If T1 is higher than initially calculated, the designer can elect to refine the design or not.
- Design the tension rods, connections and all affected bracing and foundation elements for overstrength forces Hov = 2.5 * Hy (2.0 * Hy for rings > 210 diameter) but Hov < Hel / R0.

9. Installation

It is very important to install the ring exactly at the theoretical diagonal intersection point. A test performed on one braced frame with a ring 100 mm off-centre showed degradation of the hysteresis loops and pinching behaviour. Lock washers should be used. Slight pre-tensioning of the diagonal rods from the snug tight position is recommended. If higher capacity or stiffness is needed, wider rings with multiple diagonal rods as shown in Fig. 10 can be used.

10. Conclusion

The procedure described in this paper allows designers to use a simple and ductile tension-only bracing system. The conservative design methodology described can be refined when the results from multi-storey braced frame tests are available. Larger diameter rings performed better in shake-table testing and can accommodate drift ratios greater than 1.5%.