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SEISMIC EVALUATION OF RC COLUMNS CONSIDERING EQUIVALENCY OF CIRCULAR AND SQUARE CROSS-SECTIONS

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ABSTRACT

In this paper, a simple approach for circular column design is proposed. As the current flexural and shear design methods of the RC members are mainly based upon the rectangular cross-sectional shape, the circular shaped members might be simply converted to equivalent square shape based upon equal amount of concrete and reinforcement. The experimentally verified 3D FEM called COM3D is used to investigate the seismic performance of the circular shape and its equivalent square. RC columns with both cross-sectional shapes under varied axial load and web reinforcement are laterally pushed-over to fail in different modes. The analytical results show a good agreement in seismic performance of both. As per the analytical results, the proposed approach is found satisfactory. The governing value of ductility index to ensure ductile flexural failure rather than brittle shear mode (JSCE specifications) is more than 1.0. The analytical results show that the RC members with ductility index ranging between 0.7 to 1.0 shows minimum ductile performance to survive against total collapse as they fail in flexural-shear mode. This is attributed to the longitudinal bars as part of shear reinforcement.

Keywords: Ductility, Seismic Behaviour, Circular Columns, Rectangular Columns, and Ductility Index

1. INTRODUCTION

RC axially loaded members like columns or piles may have circular cross sectional shape due to architectural desire and/or structural requirements. Indeed, axially loaded members do not carry gravitational loads alone. But due to the seismic actions, lateral load components originate causing the generation of shear and flexural forces. In order to make structures safe against earthquakes these must be made ductile enough to withstand the lateral forces while some damage may be allowed (Takase *et al*. 1999).

As the flexural design of RC circular members is following the same procedure as of the rectangular members, the detailed calculations for the circular cross section are a little bit of complexity. The shear design is based upon changing the circular cross section to the square cross one using a set of rules described by JSCE specifications while considering the main reinforcement only on the tension side,

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ignoring the side bars effects. Generally, the design of circular cross sections is more complex as compared to the rectangular cross section (Watanabe *et al*. 2011).

In this paper, a new simple method of design of RC circular members is proposed. The circular shaped members might be simply converted to equivalent square shape based upon equal amount of concrete and reinforcement. By using the nonlinear FEM program (COM3D), the circular members show similar seismic behaviour as of the equivalent square members' w.r.t different failure modes. This approach may be very beneficial for creating simplicity in the design process.

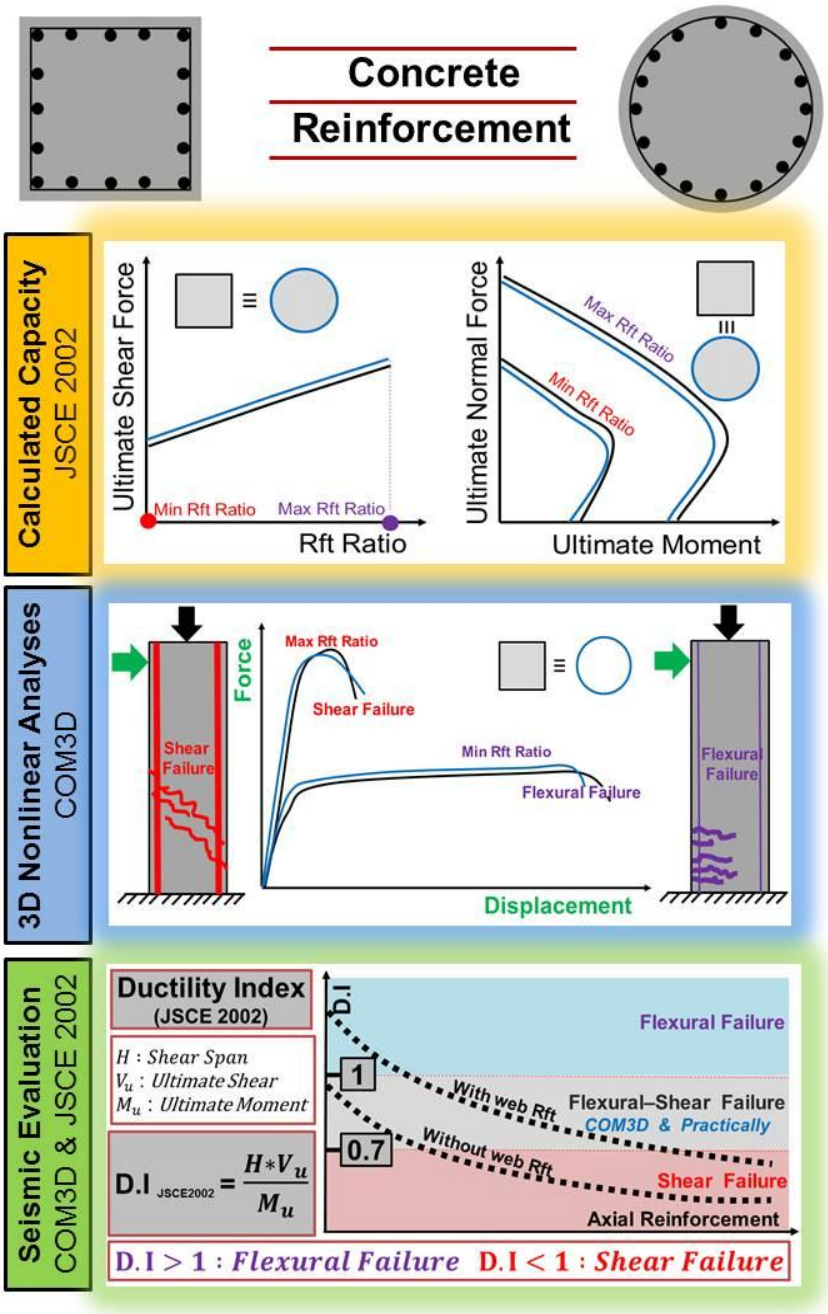

Figure 1: Overview of seismic performance of both equivalent circular and square RC columns.

The generation of shear cracks must be avoided in the axially loaded members. This may be achieved by applying the concept of ductility index denoted by several codes as,

$$\phi = \frac{V_u \cdot H}{M_u} \tag{1}$$

Where, V_u is the shear capacity of the RC member, H is the shear span length, and M_u is the flexural capacity. It is already known that if the ductility index ϕ is greater than 1.0, the failure mode will be flexural while if this value is less than 1.0 shear failure may occur (Okhovat *et al*. 2009). In practice, the columns with the ductility index less than 1.0 may not always fail in shear, but those having this value between 0.7 ~ 1.0 exhibit mix failure mode that usually starts with the flexural failure and goes to shear. This sort of failure mode also provides enough ductility so the strengthening of such RC members may not be considered urgent.

While calculating the shear strength of a cross section according to JSCE, the main reinforcement on the tension side is considered only, but in reality, the side bars also contribute towards the shear capacity. So in evaluations, they may also be rationally considered. By considering the side bars during seismic performance assessment, the criteria may change but economy may be achieved while remaining within the safety limits.

First, experimental verifications by using 3D nonlinear FE analysis program called COM3D are introduced. This analysis has been used in practice for seismic performance assessment of underground ducts, RC piles, and in-ground LNG storage tanks in consideration of soil-structure interaction under static and dynamic loading (Maekawa *et al.* 2003; Mohammed *and* Maekawa 2012). Afterwards, the parametric sensitivity analyses are conducted for verifying the proposed equivalency between circular and square sections.

2. CONSTITUTIVE MODEL

A reinforced concrete material model has been constructed by combining constitutive laws for cracked concrete and those for reinforcement. The fixed multi-directional smeared crack constitutive equations (Maekawa *et al.* 2003) are used as summarized in Figure 2. Crack spacing and diameters of reinforcing bars are implicitly taken into account in smeared and joint interface elements, no matter how large they are.

The constitutive equations of structural concrete satisfy uniqueness for compression, tension and shear transfer along crack planes. The bond between concrete and reinforcing bars is taken into account in the form of a tension stiffening model, and the space-averaged stress-strain relation of reinforcement is assumed to represent the localized plasticity of steel around concrete cracks. This RC in-plane constitutive modeling has been verified by member-based and structural-oriented experiments. Herein, the authors skip the details of the RC material modeling by referring to Maekawa *et al.* (2003).

The shear failure of RC members considering both circular and rectangular cross-sectional shapes (Watanabe *et al*. 2011) could be nicely analytically simulated by using the current COM3D constitutive modeling as shown in Figure 3.

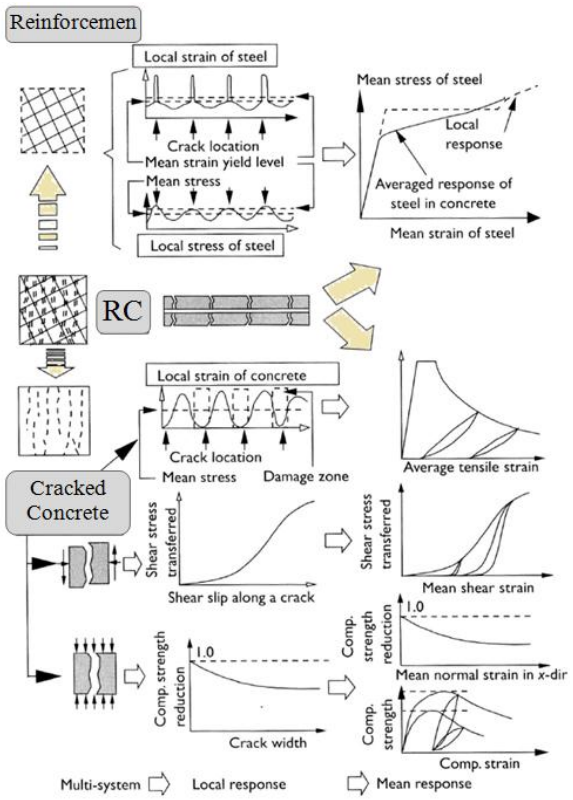

Figure 2: RC constitutive modeling (Maekawa *et al*. 2003).

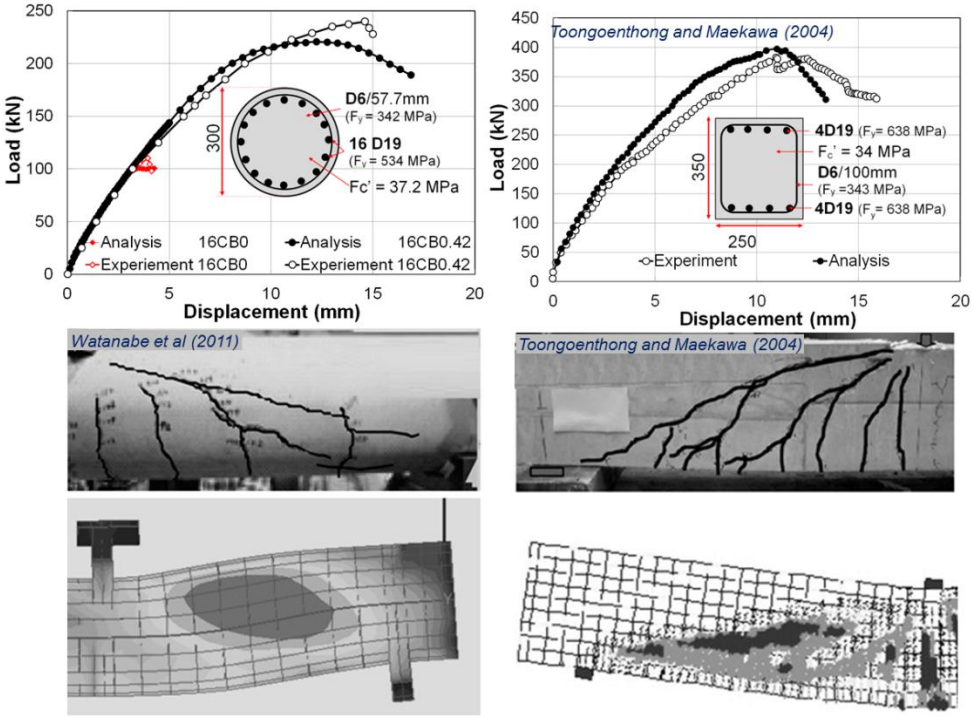

Figure 3: Experimental and analytical shear failure development of circular and rectangular RC member.

3. ANALYTICAL Model

FEM models of circular column with 1.6 meters shear span, 1 meter diameter; and an equivalent square column (0.8862m x 0.8862m) in terms of equal area of concrete and steel are considered as shown in Figure 4 to investigate the seismic performance and ductility demand of RC members. The concrete for both the types of columns, circular and square, is considered 30 MPa and the yield strength of steel is considered 400 MPa.

According to JSCE *2002*, the flexural and shear capacities of both circular and square RC cross-sections are calculated and compared as plotted in Figure 5. For comparison purpose, different configurations were analyzed with varying web reinforcement (0.0% to 0.1%), axial load level (0.0% to 30.0%) compared to the pure axial capacity and flexural reinforcement (0.5% to 4.0%). Figure 5 shows a close comparison between circular column and equivalent square one having an equal area of concrete and reinforcement.

Figure 6 shows changes in the ductility index of both circular and square RC cross-sections with varying web reinforcement, axial load and flexural reinforcement. It clearly shows the positive effect of existence of web reinforcement, and negative effect of increase in axial load and main reinforcement.

By the results shown in the Figure 5 and Figure 6, it might be established on theoretical basis that the circular columns may be designed as an equivalent square column in terms of equal area of concrete and steel as for safety.

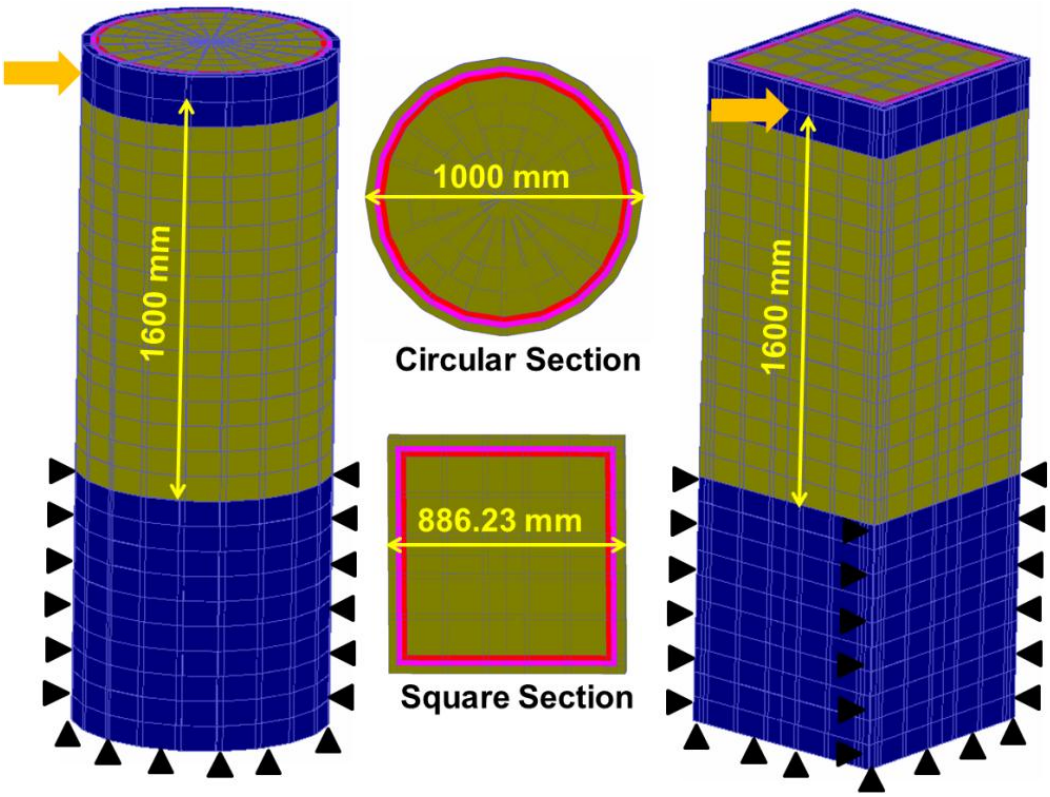

Figure 4: Circular and equivalent square RC columns.

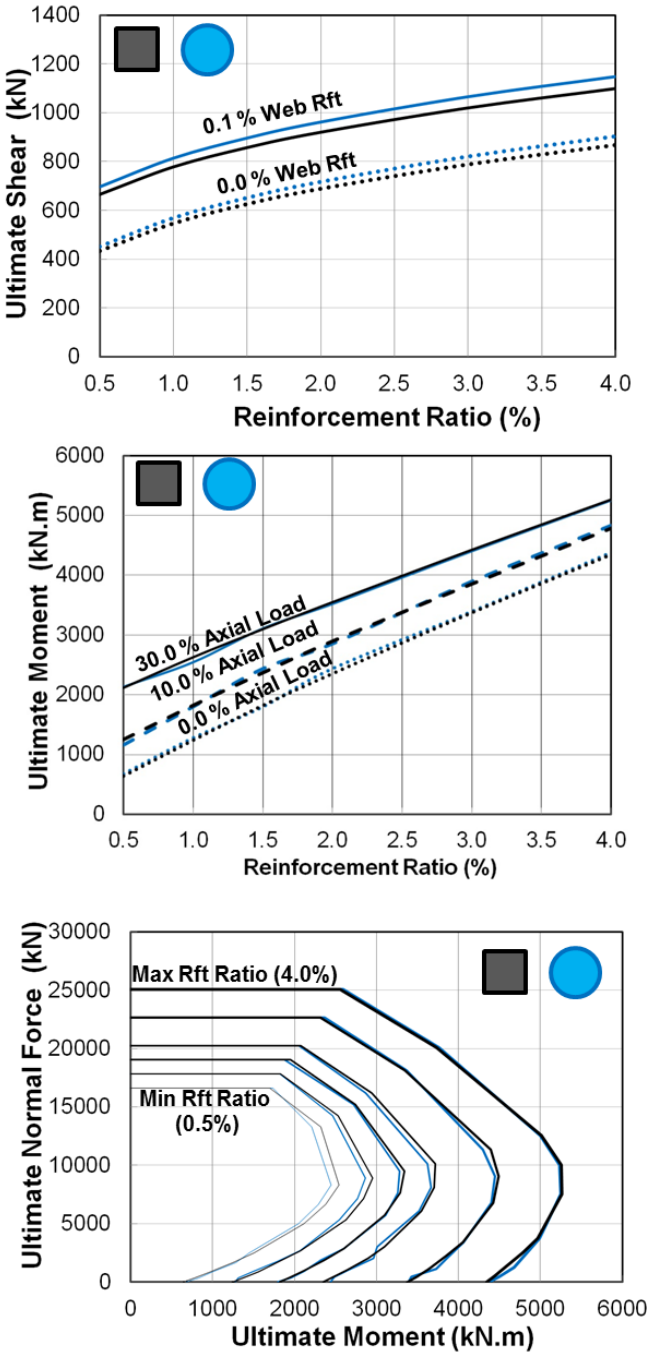

Figure 5: Ultimate capacities w.r.t varying axial load, web Rft, and main Rft.

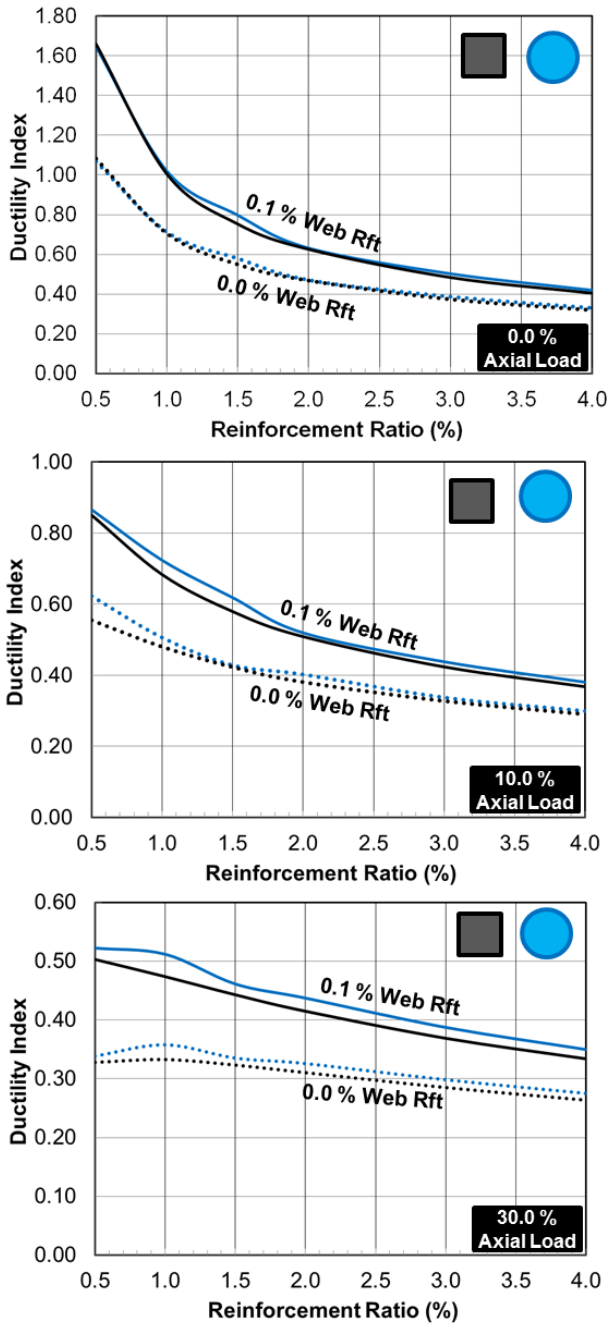

Figure 6: Ductility index w.r.t varying axial load, web Rft, and main Rft.

4. RESULTS AND DISCUSSIONS

Lateral push-over analyses are carried out to a number of circular and equivalent square RC columns to compare their seismic behavior considering the effect of increasing axial load and flexural reinforcement; and existence of web reinforcement.

Considering a nil axial load as shown in Figure 7, the load displacement relation of both cases of cross-sectional shapes are nearly similar. Web reinforcement of value 0.1% increases the value of the ductility index by 20% to 35%. Figure 8 shows a reduction in the ductility index (10% to 50%) with 10% increase in the axial load compared with nil axial load cases. The lower the main reinforcement is, the more the reduction in ductility index will be. With 30% axial load the ductility index reduced drastically by 20% to 70% compared by nil axial load cases. In such cases, concrete starts crushing in compression zone.

It is concluded that the cases with the ductility index of around 0.7 have ductility of the minimum safety to avoid brittle pure shear failure. The confinement provided by the web reinforcement improves the ductility of RC members significantly. On the contrary, the higher the axial load is applied, the lower the ductility of RC members is.

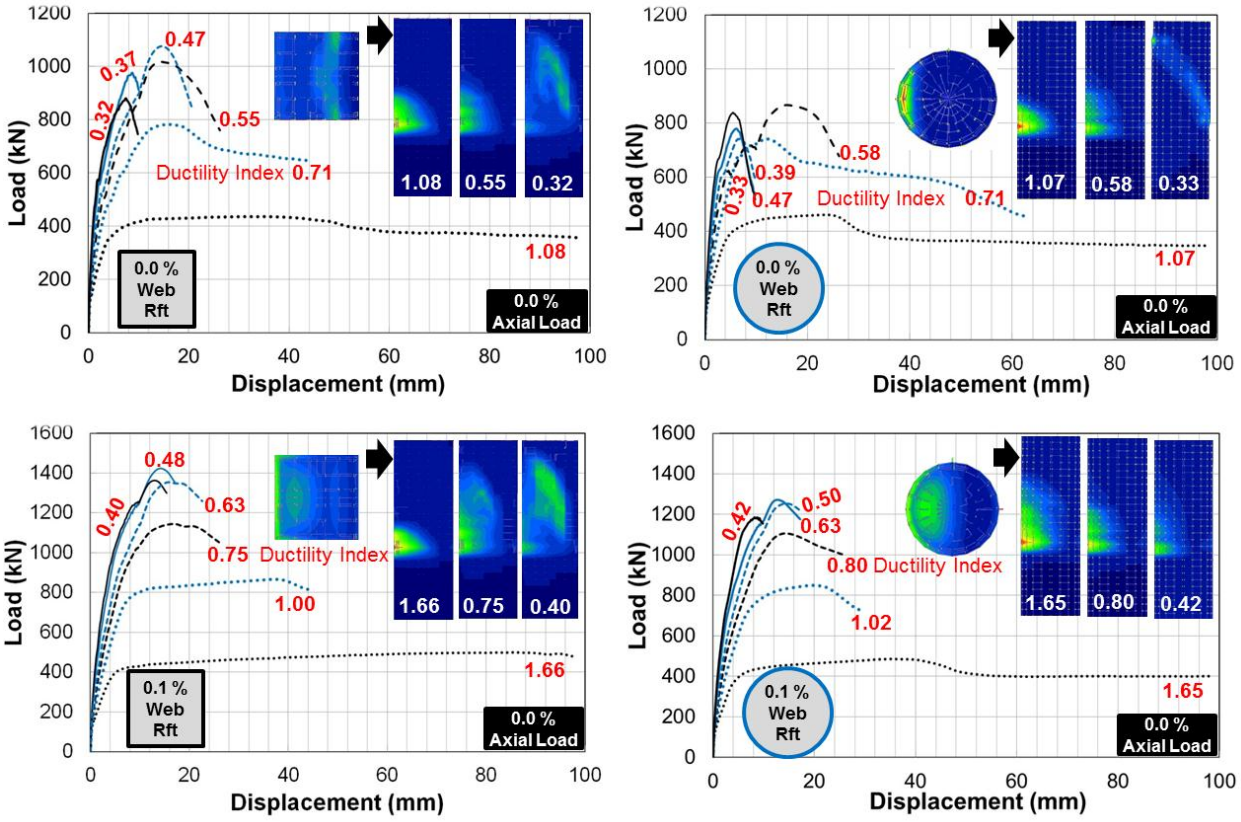

Figure 7: Lateral load-displacement relationship under nil axial load.

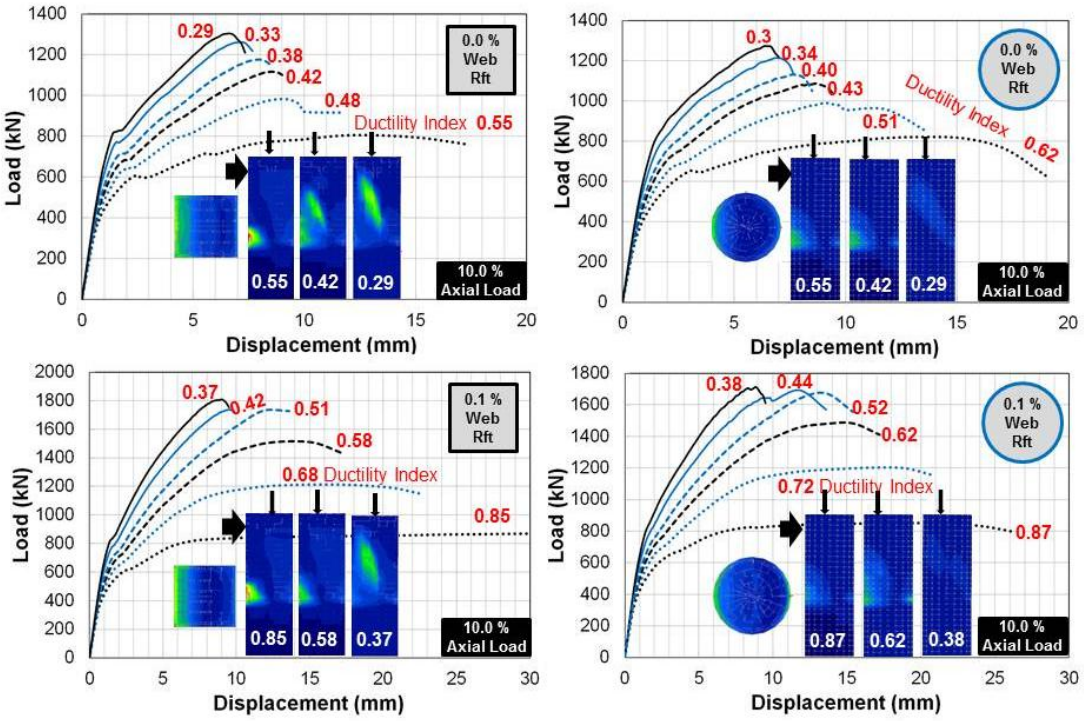

Figure 8: Lateral load displacement relationship under 10% axial load.

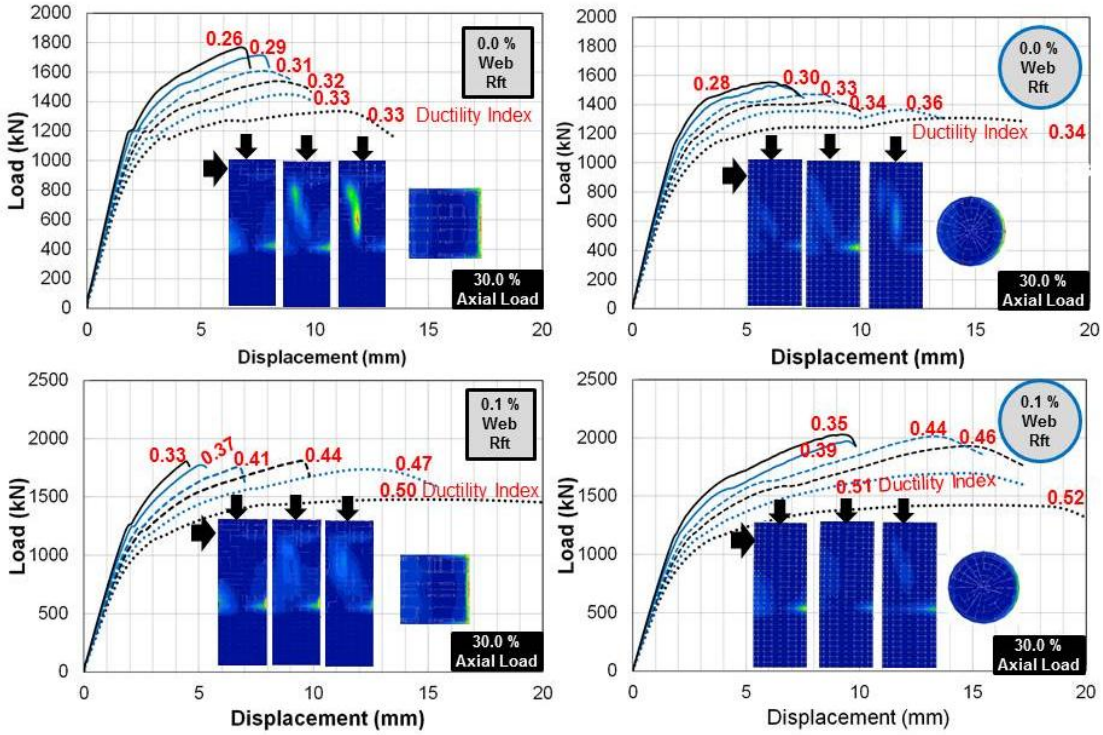

Figure 9: Lateral load displacement relationship under 30% axial load.

5. CONCLUSIONS

The circular RC columns might simply be designed as square RC columns having equal amount of concrete and reinforcement. The nonlinear behaviour of both the types of RC columns shows good agreement with respect to shear failure, shear-flexural failure and flexural failure.

For the axially loaded RC members, ductility index of around 0.7 (Figure 10) might represent a practical limit to avoid brittle pure shear failure and it may be considered as a guide in making decisions for undertaking urgent strengthening.

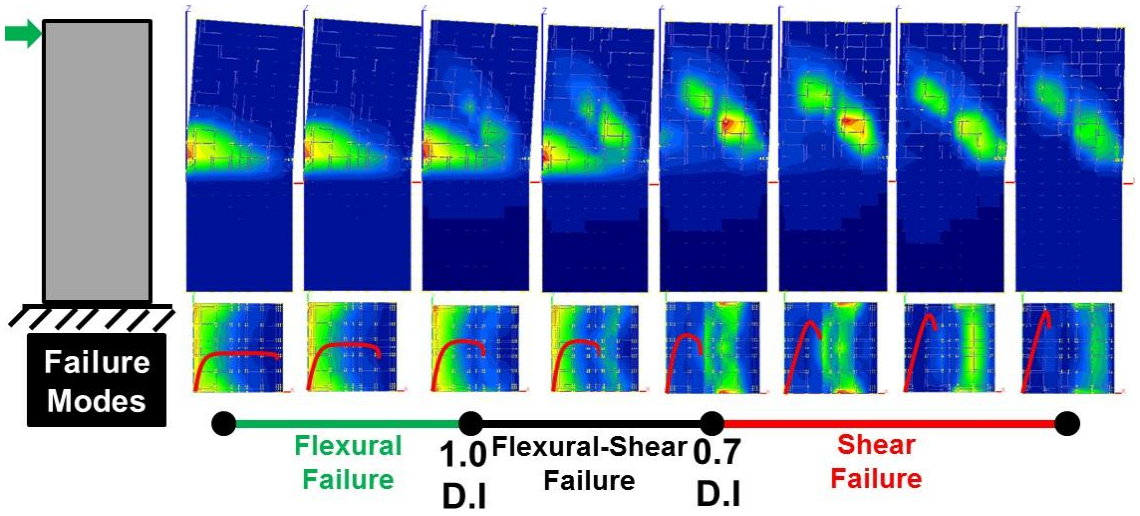

Figure 10: RC members' failure mode w.r.t ductility index.

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