Slenderness Criterion for Isolated Confined Compression Member based on EC2

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Abstract: Clause 5.8.3.1. of the Eurocode 2 (EC2) recommends a slenderness limit (λ_{lim}) for compressive members where second order effects can be ignored. This equation shall be used to study the effects of lateral reinforcements in the compressive member. The effects of spiral-shaped steel confinements on the reinforced concrete columns of 9 numbers of 125mm×125mm×500mm reinforced concrete columns, all exceeding λ_{lim} were investigated with one control column i.e. without any reinforcements, another four were confined with single spiral of 50mm pitch and the last four were confined with double spiral of 100mm pitch. This result in having the same volume of confinements introduced for all the confined concrete columns. The confinement used for the concrete were mild steel rebars of 6mm diameter. It was found that with the introduction of spiral-shaped steel confinements, the ultimate failure load of these columns exceeded the control sample and hence there is a possibility of increasing the λ_{lim} factor of EC2 by considering concrete confinements.

1 INTRODUCTION

For circular shaped reinforced concrete (RC) columns, it is common for some countries to adopt continuous spiral links. When closely spaced spiral links are adopted, it can be considered as confinements for concrete. Confinements enhance reinforced concrete structural elements in compression reducing the Poisson's effect. The Code of Practice, ACI 318-14 (ACI Committee 318, 2014) recommends the provision of spiral reinforcements' volume to approximately the strength of the column cover / shell.

There had been researches carried out on confined concrete elements which are normally short or also known as stocky. For RC columns, researches commonly carried out include adopting materials such as fibre reinforced plastic / polymer (FRP), carbon fibre reinforced polymer (CFRP), glass fibre reinforced polymer (GFRP) and concrete-filled steel tubes. There had not been many researches carried out on the effects of confinements using ordinary steel reinforcement bars on slender reinforced concrete columns. More common would be researches carried out to strengthen slender reinforced concrete columns.

In Eurocode 2 (EC2) Clause 5.8.3.1 Slenderness criterion for isolated members, it is recommended that when the slenderness, λ is less than λ_{lim} any second order effects can be ignored. This research is to investigate the effects of introducing confinements in the form of spiral shaped mild steel in reinforced concrete columns that exceeded the slenderness criterion as per EC2 (Mosley et al., 2007; Bhatt et al., 2014).

2 LITERATURE REVIEW

As early as mid-1890s, reinforcement in the form of helical / spirals were adopted in concrete elements and it was found that these elements have better resistance compared to concrete with longitudinal bars and lateral ties (Cusack, 1981). It is well noted that increased compressive strength for confined concrete would be expected since hooping actions prevent the swelling of concrete and thereby able to resist higher pressure (Considere, 1908). Stress-strain relationship for plain concrete had been developed by researchers Carreira and Chu (Carreira and Chu, 1985) while Mander, Priestley and Park developed the stress-strain relationship of confined concrere in compression (Mander et al., 1988).

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Table 1: Samples and corresponding variables used for EC2 Clause 5.8.3.1.

No. of Rebars	Area of Long. Rebar (mm^2)	ω	B	N_{ED} (kN)	λ_{lim} as per EC2 (f_{ck} (unconfined)	Actual λ used	λ_{lim} as per EC2 (f_{ck} (confined)
0	0	0	1	180.731	10.626	13.86	10.626
3	84.82	0.0665	1.0644	180.963	11.304	13.86	11.059
4	113.10	0.0887	1.0851	180.967	11.523	13.86	11.2
5	141.37	0.1109	1.1053	180.972	11.738	13.86	11.34

Yong, Nour and Nawy carried out experiments on 24 square columns with the dimensions of 150mm × 150mm × 457mm and compressive strengths of between 83.6 to 93.5N/mm2 and rectilinearly confined with lateral ties spacing varied from 25mm to 75mm. In general, the concrete columns were ductile with the introduction of the links. The peak stress and strain for both high and normal strength concrete and especially the ductility increased when more lateral steel were provided but however this was not in proportionally. However, it was found that lateral steel confinement was not as effective in low and normal strength concrete. The authors formulated an empirical model for stress-strain relationship. (Yong et al., 1988).

Mangat & Azari investigated columns of 150mm×150mm×750mm with link pitches of 125mm, 187mm and 375mm with steel fibres between 0 and 3%. The theoretical ultimate strength of the column was calculated based on the expression $P_U = 0.85\times\sigma_{cy}\times A_c + \sigma_y\times A_S$ which is proportional to the concrete characteristic strength, area of concrete, steel characteristic strength and area of steel, without taking into consideration of the partial safety factor for materials. Their research results indicated that their theoretical and experimental ultimate load only varied between 0 to 9%. They concluded that the strength of the compression members is unaffected by the link spacing or steel fibre volume (Mangat and Motamedi Azari, 1985)

Experiments on high strength concrete columns confined with single spirals and also two opposing spirals were conducted to study the axial behaviour of such elements. Monotonic axial loads were applied to the specimens. Twenty one 350mm diameter × 1000mm tall high strength concrete circular columns with different number of longitudinal rebars and four different confinement ratios were tested. It was found that the specimen with 12 longitudinal diameter 16mm rebars possessed an ultimate load of 5257kN while the specimen with 8 longitudinal diameter 16mm rebars possessed an ultimate load of 5305kN. The researchers concluded that the variation in the longitudinal rebars had not establish a trend on the effects in the confined compressive strength and strain capacity (West et al., 2016; Marvel et al., 2014). The purpose of having two opposing spirals was to facilitate easy concreting whereby if conventional single steel confinements were adopted, two opposing spirals would create the same results even if its pitch is twice that of the conventional one since the confinement volume to concrete core volume would be the same (Hindi, 2013).

BS 8110 (BSI, 1997) does not include confined concrete whereas the current code of practice, EC2 included equations for increased characteristic strength and strains (British Standards Institution, 2008). The strength of slender reinforced concrete columns under uniaxial load had been evaluated numerically using the simple transformed section concept (Chuang and Kong, 1998). In this present research, the capacity of columns exceeding the slenderness limit as per EC2 had been evaluated using the EC2's expression for confined concrete strength.

3 RESEARCH METHODOLOGY

The λ_{lim} as per EC2 Clause 5.8.3.1 is $\lambda_{lim} = 20ABC/\sqrt{n}$ and for this experiment, A and C had been taken as 0.7.

Table 1 shows the values of the variables adopted. Samples with confinements were used and all exceeded the λ_{lim} as shown in Table 1 in order to study the effects of exceeding λ_{lim}.

A total of 12 prism samples were prepared and tested under axial compression. The concrete mix was designed to have a mean 28-day compressive strength of 25N/mm^2. The cement, sand, aggregate proportion was 1:1:2 and the water cement ratio was 0.5. The influence of specimen slenderness was investigated by preparing specimens with slenderness ratios as per EC2 of 3.46, 9.24, 11.55 and 13.86 where the last slenderness ratio exceeded the limit i.e. λ_{lim}. If the older code of practice, i.e. BS 8110 were adopted, the corresponding height to least column dimension would be 1, 2.67, 3.33 and 4 respectively and since these are less than 10, it would had been classified as short based on Clause 3.8.1.3 of BS 8110. The details of the test specimens are as shown

Table 2: Specimen Properties.

Specimen (mm)	Spiral	Longitudinal Diameter 6 Rebar	Slenderness Ratio	Confinement Pitch (mm)	L / Smallest Dimension
C1 (150×150×150)	None	0	3.46		1
C2 (150×150×400)	None	0	9.24		2.67
C3 (150×150×500)	None	0	11.55		3.33
C4 (125×125×500)	None	0	13.86		4
C0R-SS	Single	0	13.86	50	4
C3R-SS	Single	3	13.86	50	4
C4R-SS	Single	4	13.86	50	4
C5R-SS	Single	5	13.86	50	4
C0R-DS	Double	0	13.86	100	4
C3R-DS	Double	3	13.86	100	4
C4R-DS	Double	4	13.86	100	4
C5R-DS	Double	5	13.86	100	4

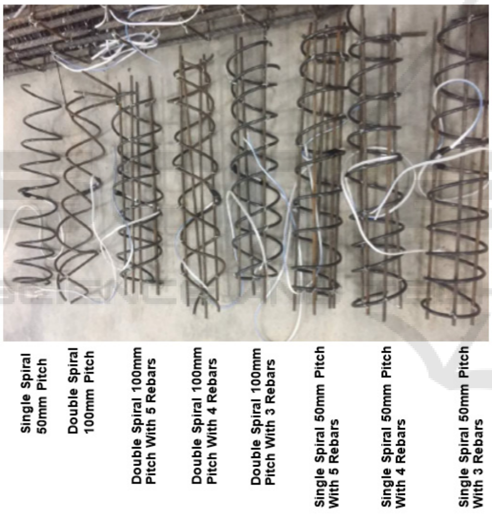

Figure 1: Single and Double Spiral Confinements Used.

in Table 2 where C1 to C4 are pure concrete control specimens but with different dimensions in order to have different slenderness ratios. The dimensions of C1 is 150mm × 150mm × 150mm, C2 is 150mm × 150mm × 400mm, C3 is 150mm × 150mm × 500mm and C4 is 125mm × 125mm × 500mm. The slenderness ratios of these are 3.46, 9.24, 11.55 and 13.86 respectively. The specimens with the suffix SS represents samples with single spiral confinements while the specimens with the suffix DS represents samples with double spiral confinements. The samples denoted with C and followed by a number and R indicates that there is additional longitudinal reinforcement bars as per the number. Diameter 6mm reinforcement bars with nominal yield stress of 250N/mm^2 were used to form both the single and double spiral confinements. The pitch of the single spiral confinements was 50mm whereas for the double spiral confinements, the pitch was 100mm. All the spirals had an outer diameter of 75mm and all samples had a concrete cover of 25mm. These confinements and main rebar configurations are as shown in Figure 1.

All samples except for C1 to C3 were installed with electronic foil strain gauges in the longitudinal and lateral directions as shown in Figure 2. All the samples were tested with an Automatic Compression Testing Machine with a maximum loading capacity of 600kN and loading was applied with a rate of 0.1kN/s. The readings of the applied load and also the strains were recorded with a data logger. The setup of the experiment is as shown in the Figure 3.

Figure 2: Installation of Strain Gauges on Concrete Specimens.

Figure 3: Experimental Setup.

4 ANALYSIS AND DISCUSSION

For Table 3, column (1) indicates the Specimen, (2) the characteristic cylindrical strength, (3) the characteristic confined concrete strength based on EC2, (4) the experimental failure load, (5) the theoretical failure load based on unconfined concrete strength, (6) the theoretical failure load based on confined concrete strength with the assumption that the column is short and (7) the slenderness ratio.

4.1 Ultimate Load

The ultimate load of a compressive member is highly dependent on the slenderness ratio that is the ultimate load is inversely proportional to the slenderness ratio. C1 for instance which was used as cube test, had a slenderness ratio of 3.46 and could achieve an ultimate load of 573.75kN while C2 with a slenderness ratio of 9.24 achieved an ultimate load of 280.13kN. C3 had a slenderness ratio of 11.55 while C4 had a slenderness ratio of 13.86. Both C3 and C4 achieved very similar ultimate loads that is 263.20kN and 273.60kN respectively.

The control specimens C2 to C4 which were plain concrete with slenderness ratios of between 9.24 and 13.86. Samples with slenderness ratio approximately above 9 and below 14 had its ultimate load reduced to approximately 50% compared to samples with slenderness ratio of approximately 3.46.

For the group of samples with single confinement having a pitch of 50mm, it was found that all specimens exceeded the control specimen's ultimate load (C4) except for specimen C4RSS which was 0.74% lower than the control specimen which should not be. C0RSS i.e. the specimen with no rebars, managed to achieve an ultimate load of 392.2kN. C3RSS, C4RSS and C5RSS reached the ultimate load of 320.7kN, 271.6kN and 388.6kN respectively.

For the group of samples with double confinement with a pitch of 100mm, it was found that all specimens exceeded the control specimen's ultimate load. C0RDS, C3RDS, C4RDS and C5RDS achieved an ultimate load of 323.2kN, 345.9kN, 443kN and 342.9kN respectively.

Column 5 of Table 3 adopted the characteristic cylindrical strength of concrete i.e. without taking into account of the confinement effects. Therefore, if a comparison of the experimental ultimate load with column 5 were to be made, it would be seen that the values of theoretical load in column 5 will underestimate the actual failure load. On the other hand, if Clause 3.1.9 of EC2 (Confined Concrete) were to be adopted, the ratio of the experimental ultimate load (column 4) to the theoretical ultimate load (column 6) varies from 5% below the theoretical value to 30% above the theoretical value (see column 10). However, it should be noted that the formulas adopted in Table 3 are based on short columns but in actual fact the columns exceeded the slenderness ratio limit as per EC2 yet was able to perform similar to a short column.

The theoretical ultimate strength from the provision of longitudinal rebars would increase as more longitudinal rebars are introduced. It would had been expected that with the increase in the number of rebars for samples C0RSS, C3RSS, C4RSS and C5RSS, a corresponding higher experimental ultimate load would be obtained. However, for C5RSS, it possessed a lower ultimate load compared to the sample with no reinforcement bars i.e. C0RSS. Similarly, it would had been expected that C5RDS possesses a higher ultimate load compared to the sample C3RDS and C4RDS. However, both C3RDS and C4RDS exceed C5RDS's ultimate load.

This is similar to the experiment carried by Johnathan West, Ahmed Ibrahim and Riyadh Hindi, Analytical compressive stress-strain model for high strength concrete confined with cross spiral whereby for their single spiral specimen with 12 longitudinal diameter 16mm rebars had a lower ultimate load compared to the sample with 8 longitudinal rebars.

4.2 Axial and Lateral Strain vs. Stress

The following show the axial and lateral strain vs. stress curve of all the of the control sample C4, C0RSS, C3RSS, C5RSS, C0RDS, C3RDS and C5RDS. All strain units are multiplied by $\times 10^{-6}$. The strain gauge reading of C4 indicated that the longitudinal strain as positive i.e. tension and the lateral strain as negative i.e. compression. It is likely that the applied load had not been perfectly concentric.

Table 3: Test results of column specimens.

Specimen	f_{ck} (N/mm^2)	$f_{ck,\,conf}$ (N/mm^2)	Experimental	Theoretical $P_U = 0.85f_{ck}A_c + f_yA_s$	Theoretical $P_U = 0.85\, f_{ck,conf}\, A_{conf} + 0.85f_{ck}(A_{gross} - A_{conf}) + f_yA_s$	Slenderness Ratio	(4) / (6)	Poisson's Ratio (at 60% Ultimate Load)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
C1	20.4		573.75	-	-	3.46		
C2	20.4		280.13	390.15	-	9.24		
C3	20.4		263.20	390.15	-	11.55		
C4	20.4		273.60	270.94	270.94	13.86		0.14
C0RSS	20.4	32.37	392.2	270.94	315.89	13.86	1.24	0.24
C3RSS	20.4	32.37	320.7	292.14	337.09	13.86	0.95	0.16
C4RSS	20.4	32.37	271.6	299.21	344.16	13.86	0.78	-
C5RSS	20.4	32.37	388.6	306.28	351.23	13.86	1.11	0.16
C0RDS	20.4	32.37	323.2	270.94	315.89	13.86	1.02	0.13
C3RDS	20.4	32.37	345.9	292.14	337.09	13.86	1.03	0.07
C4RDS	20.4	32.37	443	299.21	344.16	13.86	1.30	0.83
C5RDS	20.4	32.37	342.9	306.28	351.23	13.86	0.98	0.25

From the graph of C4RSS it was noticed that when the specimen experienced a stress of approximately 11N/mm2, the reading then reduced to about 8.5N/mn2. Also, the specimen C4RDS had both longitudinal and lateral strains as tension. These graphs were not included.

For rest of the curve, it can be seen that a V-shape curve is formed. In general, it can be seen that the horizontal distance from the peak of the axial strain curve to the vertical axis is larger than the horizontal distance from the peak of the lateral strain curve to the vertical axis. Column 8 of Table 3 show the Poisson's Ratio of the control and the samples.

4.3 Slenderness Limit λ_{lim} and Actual Slenderness λ

Even though the samples with confinements had exceeded the slenderness limit as per EC2, their theoretical loads had been calculated as shown in Column (5) of Table 3 and ignoring the partial factors of safety (1.5). The compressive design strength, $N_{ud} = 0.85 \times f_{ck} \times A_c + A_s \times f_{yk}$. If no longitudinal reinforcements were adopted, the equation now becomes $N_{ud} = 0.85 \times f_{ck} \times A_c = 270.94$ kN for specimen C4. If the similar ultimate load is obtained based on BS 8110, it would be $N_{ud} = 0.67 \times f_{cu} \times A_c = 266.96$ kN. Columns C2, C3 and C4 achieved failure loads of 280.13, 263.20 and 273.60kN respectively which was ±3.3% of the control's ultimate load. C3 and C4 possess the slenderness ratios of 11.55 and 13.86 respectively which exceeded their slenderness limits of 10.626. Sample C2 possess a slenderness ratio of 9.24 which is below the slenderness limit. However, the experimental ultimate loads of C2, C3 and C4 were very close suggesting that even though the slenderness limit is 10.626, it could actually be increased to 13.86. Furthermore, it could be seen in Table 3 that if confined concrete strength together with the assumption of a short column, the experimental values were close to the theoretical values suggesting that the actual slenderness ratio of 13.86 would be safe to be considered as short column.

The average λ_{lim} for the 3 rebars, 4 rebars and 5 rebars is 11.52. Based on the equation $\lambda_{lim} = 20ABC/\sqrt{n}$, the product of the variables ABC gives 0.532 (B was taken as an average). Since the samples exceeded the control C4's ultimate load, the factor 20 in the equation can be increased to 24 or $\lambda_{lim} = 24ABC/\sqrt{n}$ when closely spaced confinements of 50mm were adopted.

When concrete confinements in the form of single spiral with a pitch of 50mm were introduced to a 125 × 125 × 500 concrete sample C0RSS with no longitudinal rebars, the failure load achieved 392.2kN. This is more than the expected failure load of a short column i.e. 270.94kN. In other words, with the introduction of concrete confinements, it is can be acceptable to relax the λ_{lim} as per clause 5.8.3.1 of EC2. Similarly, the same limit $\lambda_{lim} = 24ABC/\sqrt{n}$

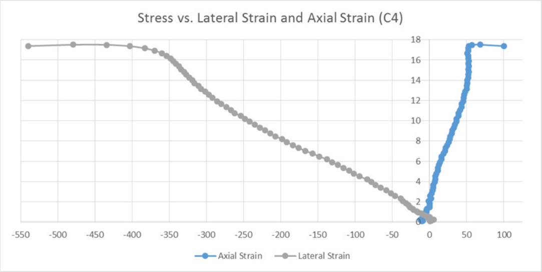

Figure 4: Stress vs. Lateral and Axial Strain for C4.

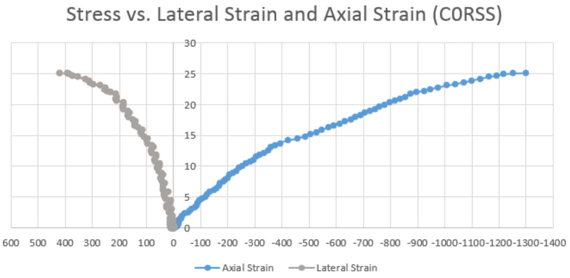

Figure 5: Stress vs. Lateral and Axial Strain for C0RSS.

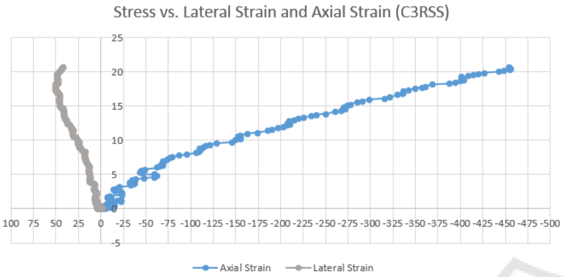

Figure 6: Stress vs. Lateral and Axial Strain for C3RSS.

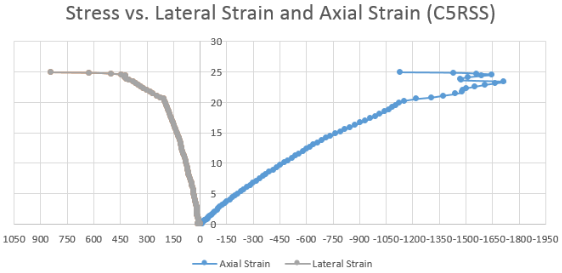

Figure 7: Stress vs. Lateral and Axial Strain for C5RSS.

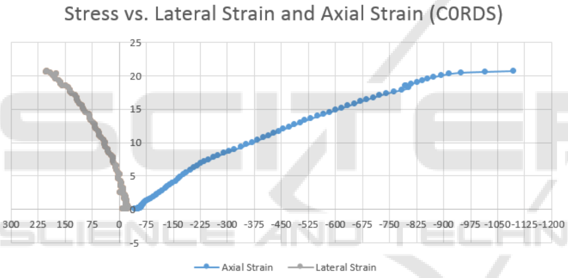

Figure 8: Stress vs. Lateral and Axial Strain for C0RDS.

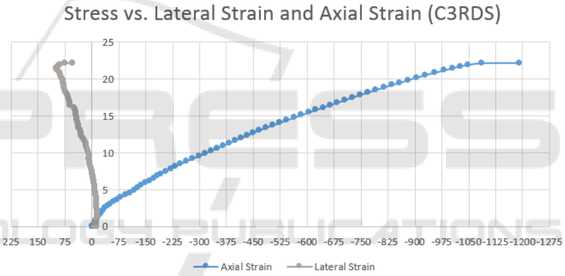

Figure 9: Stress vs. Lateral and Axial Strain for C3RDS.

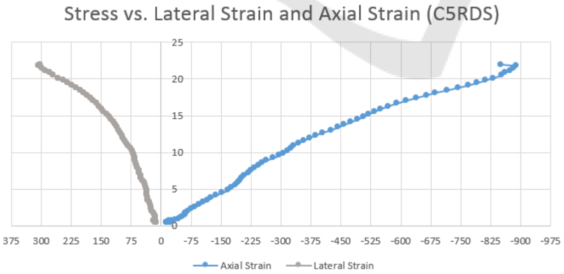

Figure 10: Stress vs. Lateral and Axial Strain for C5RDS.

can be applied for the samples with double confinements with a pitch of 100mm or with the equivalent confinement volume.

Clause 3.8.1.3 of BS 8110 adopted a ratio of height to smallest unbraced column dimension and if this ratio is below 10, then the column would be assumed short. The same criteria applies with the older Code of Practice i.e. CP114. The sample C4 have a height / least dimension ratio of 4 and hence is classified as short based on the older codes of practice i.e. BS 8110 and CP114. The failure load of C4 based on short column assumption is also still valid since the experimental and theoretical values are the ±2.66kN. However for samples C2 and C3, the theoretical exceeded the experimental values by 110.02kN and 126.95kN respectively which is not favourable.

4.4 Confined Compressive Strength with Slenderness Ratio of 13.86

All the samples with confinements exceeded the limit, λ_{lim} as recommended by Clause 5.8.3.1 of EC2 and comparing the control sample C4 with the rest of the samples, all samples except for C4RSS exceeded the control column C4 by between 17% to 43% for the single spiral confinement and 18% to 62% for the double confinement. On average, the experimental values exceed the control by 25% for the single spiral confinement and 33% for the double confinement.

5 CONCLUSION

The introduction of confinements especially closely spaced confinements such as confinements at 25mm centres will enhance the ultimate strength of the concrete column even though columns with their slenderness ratios exceeding the limit as recommended by EC2. It is proposed that the slenderness limit $\lambda_{lim} = 20ABC/\sqrt{n}$ be increased to $\lambda_{lim} = 24ABC/\sqrt{n}$.

NOMENCLATURE

$A = 1/(1 + 0.2\phi_{ef})$
$B = \sqrt{1 + 2\omega}$
$C = 1.7 - r_m$
ϕ_{ef} = the effective creep ratio and if this is not known then A is assumed as 0.7.
ω = the ratio of products $A_s f_{yd}$ to $A_c f_{cd}$.
n = the ratio of N_{Ed} to $A_c f_{cd}$.
N_{ED} = design axial load which was taken based on the amount of longitudinal reinforcement bars and also concrete cross section

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REFERENCES

ACI Committee 318, 2014. *ACI 318-14 Building Code Requirements for Structural Concrete and Commentary*, American Concrete Institute.

Bhatt, P., Mac Ginley, T.J. & Choo, B. S., 2014. *Reinforced concrete design to Eurocodes*.

British Standards Institution, 2008. *Eurocode 2: design of concrete structures: British standard.* , (June).

BSI, 1997. *Structural use of concrete — Part 1: Code of practice for design and construction*.

Carreira, D.J. & Chu, K.-H., 1985. “Stress-Strain Relationship for Plain Concrete in Compression”, ACI Journal, Vol. 82, No. 6, pp.797–804.

Chuang, P.-H. & Kong, S.-K., 1998. “Strength of Slender Reinforced Concrete Columns”, *Journal of Structural Engineering*, Vol. 124, No. 9, pp.992–998.

Considere, A., 1908. *Experimental Researches on Reinforced Concrete Second*, McGraw Publishing Company, New York.

Cusack, P., 1981. *Reinforced Concrete in Britain: 1897 - 1908*. University of Edinburgh.

Hindi, R., 2013. *Behavior of Concrete Columns Confined With Cross Spirals Under Different Loads*. ASCE, pp.1662–1672.

Mander, J., Priestley, M. & Park, R., 1988. “Theorectical stress-strain model for confined concrete”, *Journal of Structural Engineering*, Vol. 114, No. 8, pp.1804–26.

Mangat, P.S. & Motamedi Azari, M., 1985. “Influence of steel fibre and stirrup reinforcement on the properties of concrete in compression members”, *International Journal of Cement Composites and Lightweight Concrete*, Vol. 7, No. 3, pp.183–192.

Marvel, L., Doty, N., Lindquist, W. & Hindi, R., 2014. “Axial behavior of high-strength concrete confined with multiple spirals”, *Engineering Structures*, Vol. 60, pp. 68–80.

Mosley, B., Bungey, J. & Hulse, R., 2007. *Reinforced Concrete Design to Eurocode 2*.

West, J., Ibrahim, A. & Hindi, R., 2016. “Analytical compressive stress-strain model for high-strength concrete confined with cross-spirals”, *Engineering Structures*, Vol. 113, pp. 362–370.

Yong, Y.-K., Nour, M.G. & Nawy, E.G., 1988. “Behavior of Laterally Confined High-Strength Concrete under Axial Loads”, *Journal of Structural Engineering*, Vol. 114, No. 2, pp.332–351.