CONSTITUTIVE LAWS FOR CONFINED CONCRETE SUBJECTED TO CYCLIC LOADING: STATE-OF-THE-ART

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ABSTRACT

This paper reviews the existing characteristic constitutive laws for compression confined concrete subjected to cyclic loading. Some of the models are based on the experimental tests while some are based on the analytical investigation. Stress-strain models are defined by considering some components such as envelope curve, unloading and reloading curves.

Keywords: confined concrete, constitutive law, unloading, reloading, cyclic loading.

1. INTRODUCTION

The knowledge of stress-strain behavior and fracture mechanism of concrete constituents is required to forecast how concrete acts under various types of loads (Washa, 1950). Examining the stress-strain diagram of reinforced concrete (RC) elements subjected to compression make it conceivable to determine the properties of RC members such as strength and ductility (Chen, 2013). This knowledge can only be obtained through testing and monitoring so that the performance can be studied and new theories can be introduced (Washa, 1950).

Recently, the introduction of many understandable and more complex models under numerous stress states to explain the behavior of concrete has been on the increased. However, most of these developed models have larger theoretical significance than practical importance but they solely explain some selected parts of concrete behavior and their application is limited to the basic pragmatic application. Aslani and Jowkarmeimandi (2012). Sadeghi (1994, 1995, 2001, 2014, 2017a) produced a finite element model to eliminate the issue attributed to scale impact named "Biaxial Bending Column Simulation" where the column models were assessed based on the practical and simulated test. Along these lines, the presented nonlinear laws for stress-strain regarding confined concrete subjected to load of cyclic nature was changed and approved.

In a research conducted by Konstantinidis et al. (2004), an analytical model was developed for the case when a cyclic load is applied to a concrete and it is found out that what is more significant is the precise description of envelope curve instead of the pattern of reloading and unloading branches. Verification of this can be seen from the stress-strain graph of a cubic sample having a strength of 57 MPa under frequent uniaxial compression, along with the stress-strain diagram of the same sample subjected to increasing monotonic compressive load. In addition, it can be observed that the curve of the stress-strain diagram of a high strength concrete subjected to cyclic loading meets the stress-strain curve of a monotonic loading. A study by Karsan and Jirsa (1969) reported a similar outcome for concrete of normal strength. Other criteria that need to be considered are the increase in the plastic strain of concrete along with the impact of confinement because of transverse reinforcement.

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In this paper main concepts of the proposed constitutive laws for confined and unconfined concretes are submitted. For more information and the formulas and the details as well as the application of these laws, the readers are referred to the reference list given at the end of this manuscript.

2. EXISTING CHARACTERISTIC MODELS FOR CYCLIC LOADING

Descriptions of the findings of the researchers are reviewed. There are some phases on concrete constitutive law subjected to cyclic loading named; envelope curve, unloading and reloading curve.

2.1 Models of Sadeghi and Nouban

The following constitutive law is proposed to simulate numerically the behavior of confined concrete elements discrete within the sections of RC members.

2.1.1 Constitutive law for confined concrete subjected to cyclic loading

2.1.1.1. Stress-strain curves for confined and unconfined concretes subjected to monotonic loading

The stress for the loading case can be found by using the envelope curve in the cases of confined and unconfined concretes.

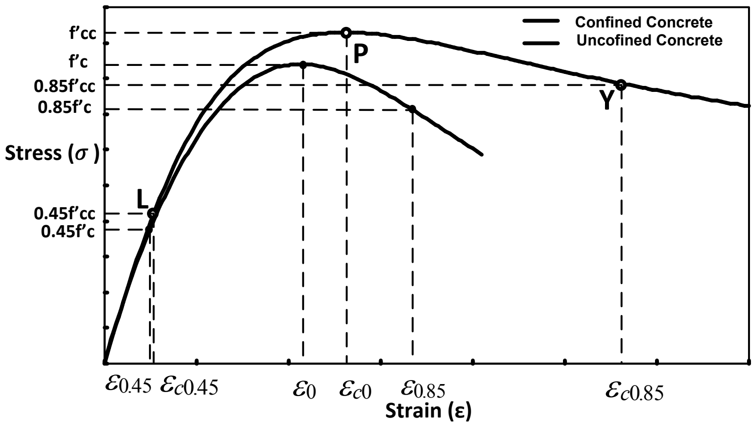

Figure 1. Stress-strain curves for confined and unconfined concretes subjected to monotonic loading (Envelope curve for cyclic loading cases)

2.1.1.2. Unloading curve

As shown in Figures 2 to 4, unloading may occur either from the envelope curve or from a phase of reloading. In both cases, the equation (1) gives the stress-strain curve for unloading.

$$\sigma = [A_U\left(\frac{\varepsilon}{\varepsilon_{co}}\right)^3 + B_U\left(\frac{\varepsilon}{\varepsilon_{co}}\right)^2 + C_U\left(\frac{\varepsilon}{\varepsilon_{co}}\right) + D_U]f'_{cc} \qquad (1)$$

The four unknown factors A_U, B_U, C_U, and D_U can be found by applying the coordinates and slopes of two extreme points on the unloading curve.

a) Unloading from the envelope curve

In the case of unloading from the envelope curve as illustrated in Figure 2, to find the unknown factors A_U, B_U, C_U and D_U, the coordinates and slopes at points $A(\varepsilon_A, \sigma_A)$ and $B(\varepsilon_p, 0)$ are used.

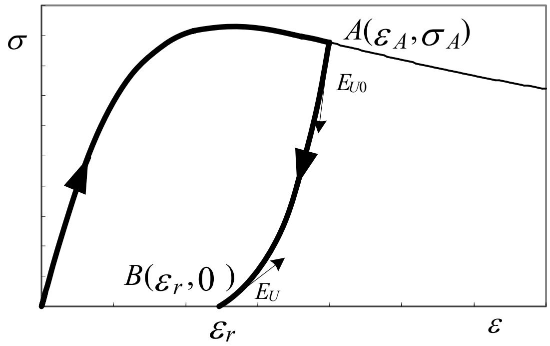

Figure 2. Illustration of an unloading case from the envelope curve.

b) Unloading from a phase of reloading case

In the unloading case from a phase of reloading, depending on the coordinates of unloading point (C or D) comparing with the coordinates of point $A(\varepsilon_A, \sigma_A)$, different moduli are used as given below and as shown in Figures 3 and 4.

b1) Unloading from a point C where $\varepsilon_C < \varepsilon_A$

- **Point $C(\varepsilon_C, \sigma_C)$:**

The value of unloading tangent modulus (E_{UC}) at point C is obtained by linear interpolation between the modulus E_{U0} at point A and E_U at point B.

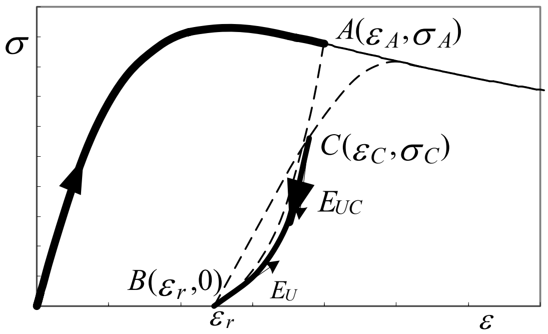

Figure 3. Unloading case from a point C on reloading curve where $\varepsilon_C < \varepsilon_A$.

b2) Unloading from a point D where $\varepsilon_D > \varepsilon_A$

For the path shown in Figure 4, the two points D and E that the curve DE passes through them are determined as follows:

- **Point D(ε_D, σ_D):**

The value of the unloading tangent modulus (E_{UD}) at point D is obtained by linear interpolation between the modulus E_{U0} at point F and E_U at point E. The point F is defined as the intersection of the line of slope $1.5E_{c0.45}$ passing from point D with the envelope curve. By applying the coordinates of point F instead of the coordinates of point A, equation (2) allows the determination of the unloading modulus at point F.

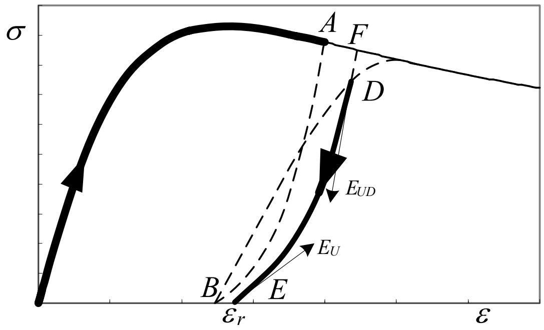

Figure 4. Unloading case from a point D on the reloading curve where $\varepsilon_D > \varepsilon_A$.

2.1.1.3. Reloading curve

Equation (2) is used for the reloading curve:

$$\sigma = [A_R\left(\frac{\varepsilon}{\varepsilon_{co}}\right)^3 + B_R\left(\frac{\varepsilon}{\varepsilon_{co}}\right)^2 + C_R\left(\frac{\varepsilon}{\varepsilon_{co}}\right) + D_R]f'_{cc} \quad (2)$$

The four unknown factors A_R, B_R, C_R, and D_R are found by applying the coordinates and slopes of the two extreme points of the reloading curve.

As shown in Figures 5 and 6, reloading from zero stress and reloading from an unloading path are considered in two different cases as follows:

a) Reloading case from a zero-stress status (plastic residual strain)

For the path BG shown in Figure 5, the two points B and G that the curve BG passes through them are determined as follows:

Point B((ε_r, 0):

The coordinates of point B have been determined in the previous steps.

The modulus E_{R0} is the tangent modulus on the envelope curve at point G.

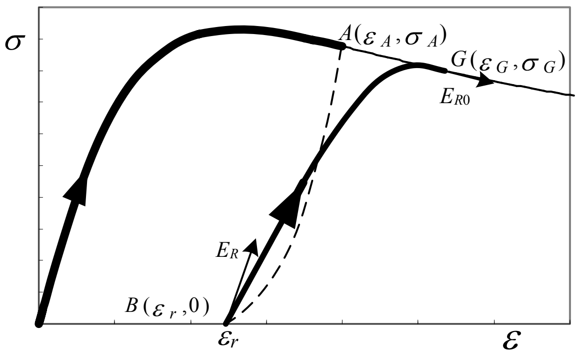

Figure 5. Reloading case from a point of zero stress

Reloading case from an unloading path

For the trajectory HI shown in Figure 6, the coordinates and slopes of the two points H and I at the starting and finishing points of the curve HI are determined as follows:

Point H(ε_H, σ_H):

The coordinates of point H have been determined in the previous step.

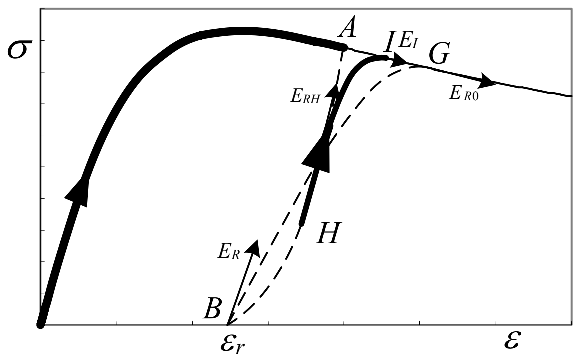

Figure 6. Reloading case from a point on the unloading path.

2.2 Models of Karsan and Jirsa

A research was carried by Karsan and Jirsa (1969) to research the concrete behave subjected to compressive cyclic loadings.

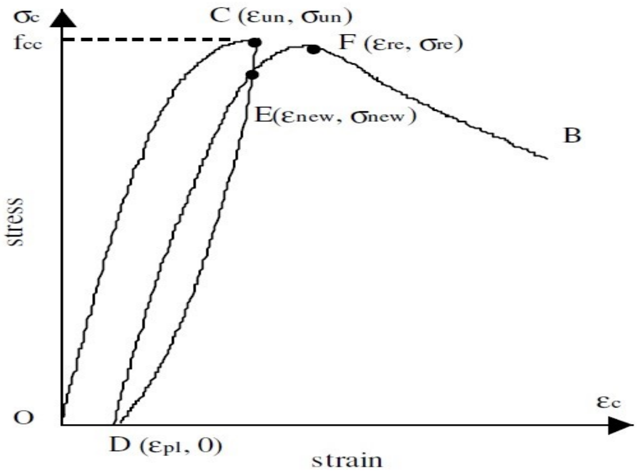

Figure 7. Stress-strain diagram of cyclically loaded concrete (Karsan and Jirsa, 1969)

Envelope Curve

$$\sigma = 0.85 f_c \frac{\varepsilon}{\varepsilon_{ccl}} e^{\left(1-\frac{\varepsilon}{\varepsilon_{ccl}}\right)} \tag{3}$$

Unloading Curve

$$\sigma = f_c \left[0.093 \left(\frac{\varepsilon_{un}}{\varepsilon_{ccl}}\right)^2 + 0.091 \left(\frac{\varepsilon_{un}}{\varepsilon_{ccl}}\right)\right] \tag{4}$$

Reloading Curve

$$\sigma = f_c \left[0.145 \left(\frac{\varepsilon_{un}}{\varepsilon_{ccl}}\right)^2 + 0.13 \left(\frac{\varepsilon_{un}}{\varepsilon_{ccl}}\right)\right] \tag{5}$$

For the definition of the symbols, please refer to the notation Section at the end of this paper.

The details of these formulas are given in the references: (Karsan and Jirsa, 1969); (Aslani and Jowkarmeimandi 2012) and the application of these formulas are given in the references: (Zhang et al., 2018); (Konstantinidis et al., 2004); (Youssef and Moftah, 2007).

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2.3 Models of Martinez-Rueda

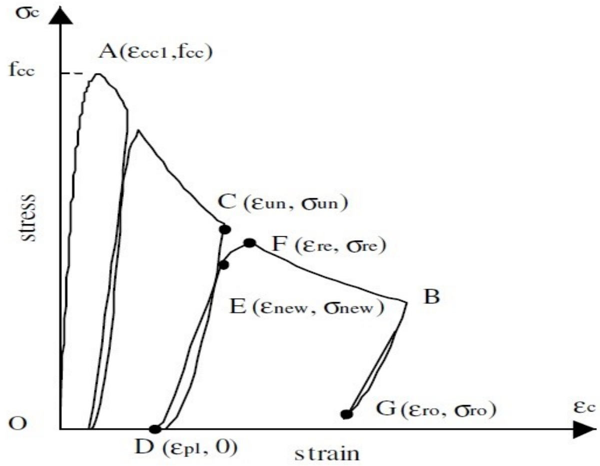

Figure 8. Stress-strain diagram of concrete subjected to cyclic loading (Martinez-Rueda, 1997)

Martinez-Rueda (1997) did some modifications to Mander's et al. (1989) model on the fact that the experienced absence of numerical balance of Mander's model for huge displacements, that results to convergence issues if which caused joining issues when executed into a non-straight program following a fiber component approach. In addition, the plastic strain of low, halfway and the high strain was modified and taking into account the relieving of concrete as strain advances. The strains greater than ε_{un} was converted to a line that falls in between the strong point and point of return. To make up for the absence of a steady change between the branches of reloading and the envelope, the average value was given to returning strain between ε_{new} and ε'_{re}, which is gotten utilizing the experimental equation of Karsan and Jirsa (1969).

Envelope Curve

$$\sigma = \frac{f'_{cc} x r}{r-1+x^r} \tag{6}$$

Where:

$$x = \frac{\varepsilon_c}{\varepsilon_{ccl}} \tag{7}$$

$$r = \frac{E_c}{E_c - E_{cl}} \tag{8}$$

Reloading curve

$$\sigma_{new} = \frac{0.9 f_{cc} \frac{\varepsilon_c}{0.9\varepsilon_{cc}} r}{r-1+x^r} \tag{9}$$

Unloading Curve

$$\sigma = \sigma_{un} \left(\frac{\varepsilon - \varepsilon_{pl}}{\varepsilon_{un} - \varepsilon_{pl}}\right)^2 \tag{10}$$

Reloading Curve

First branch: $\sigma = \sigma_{ro} + E_r(\varepsilon - \varepsilon_{ro})$ (11)

Second branch: $\sigma = \sigma_{new} + E_{re}(\varepsilon - \varepsilon_{re})$ (12)

$$\sigma_{cr} = \frac{2.5 f_{cc} r}{r-1+2.5^r} \tag{13}$$

For the definition of the symbols, please refer to the notation Section at the end of this paper.

The details of these formulas are given in the reference: (Martinez-Rueda, 1997) and the application of these formulas are given in the references: (Martinez-Rueda, 1997); (Konstantinidis et al., 2004).

2.4 Models of Mander et al.

Mander et al. (1989) proposed a technique that was utilized to show how both confined and unconfined concretes behave. A unified model for confined concrete subjected to cyclic and monotonic compressive loading. This model is a streamlined variant of the Karsan and Jirsa model shows that design the capacity of concrete to convey about tensile stresses. A stress-strain relationship is constructed using a single equation developed by the model. Due to its generalization, research and design have been presently adopted extensively by this approach. An equation by Popovics (1973) gives the envelope curve incorporating the impact of confinement. The unloading branches connect the point C (strain reversal point) to point of full reversal i.e. point D having zero slope. Reloading occurs on two branches. Strains lesser than highest strain observed a line was inserted amid point of reloading (point G) and the descending point of strength (point E). Strain bigger than maximum strain joins the degrading point of strength (point E) with a parabolic curve to the point of returning (point F) along the envelope. There is a varying equation of inelastic strain when the highest strain observed is altered, this occurs on the second reloading branch or the envelope.

Envelope Curve

$$\sigma = \frac{f'_{cc} x r}{r-1+x^r} \quad (14)$$

Where:

$$x = \frac{\varepsilon_c}{\varepsilon_{cc}} \quad (15)$$

$$r = \frac{E_c}{E_c - E_{cl}} \quad (16)$$

Reloading curve

$$\sigma_{new} = 0.92\sigma_{un} + 0.08\sigma_{ro} \quad (17)$$

Unloading Curve

$$\sigma = \sigma_{un} - \frac{\sigma_{un}\left(\frac{\varepsilon-\varepsilon_{un}}{\varepsilon_{pl}+\varepsilon_{un}}\right)\frac{bcE_c}{bcE_c-E_{cl}}}{\frac{bcE_c}{bcE_c-E_{cl}}-1+\left(\frac{\varepsilon-\varepsilon_{un}}{\varepsilon_{pl}+\varepsilon_{un}}\right)^{\frac{bcE_c}{bcE_c-E_{cl}}}} \quad (18)$$

Unloading and Reloading Curve

First branch: $\sigma = \sigma_{ro} + E_r(\varepsilon - \varepsilon_{ro})$ (19)

Second branch: $\sigma = \sigma_{re} + E_r(\varepsilon - \varepsilon_{re}) + A(\varepsilon - \varepsilon_{re})^2$ (20)

For the definition of the symbols, please refer to the notation Section at the end of this paper.

The details of these formulas are given in the references: (Mander et al., 1989); (Karsan and Jirsa, 1969); (Popovics 1973); (Aslani and Jowkarmeimandi 2012) and the application of these formulas are given in the references: (Youssef and Moftah, 2007); (Konstantinidis et al., 2004).

2.5 Models of Lam and Teng

Lam et al. (2006) did cyclic compressive unloading tests with 3 repeated cycles and they utilized the unloading history impact on the stress-strain curve.

Envelope Curve:

$$\sigma_C = E_c\varepsilon_c - \frac{(E_c-E_2)^2}{4f'_{co}}\varepsilon_c^2 \quad for\ 0 \le \varepsilon_c \le \varepsilon_t \tag{21}$$

$$\sigma_C = f'_{co} + E_2\varepsilon_c \quad for\ \varepsilon_t \le \varepsilon_c \le \varepsilon_{cu} \tag{22}$$

Unloading Curve:

$$\sigma_c = a\varepsilon_c^{\eta} + b\varepsilon_c + c \tag{23}$$

With

$$a = \frac{\sigma_{un} - E_{un,0}(\varepsilon_{un} - \varepsilon_{pl})}{\varepsilon_{un}^{\eta} - \varepsilon_{pl}^{\eta} - \eta\varepsilon_{pl}^{\eta-1}(\varepsilon_{un} - \varepsilon_{pl})} \tag{24}$$

$$b = E_{un,0} - \eta\varepsilon_{pl}^{\eta-1}a \tag{25}$$

$$c = -a\varepsilon_{pl}^{\eta} - b\varepsilon_{pl} \tag{26}$$

Where:

$$\eta = 350\varepsilon_{un} + 3 \tag{27}$$

$$E_{un,0} = \min\begin{cases}\dfrac{0.5fc'_{co}}{\varepsilon_{un}}\\ \dfrac{\sigma_{un}}{\varepsilon_{un}-\varepsilon_{pl}}\end{cases} \tag{28}$$

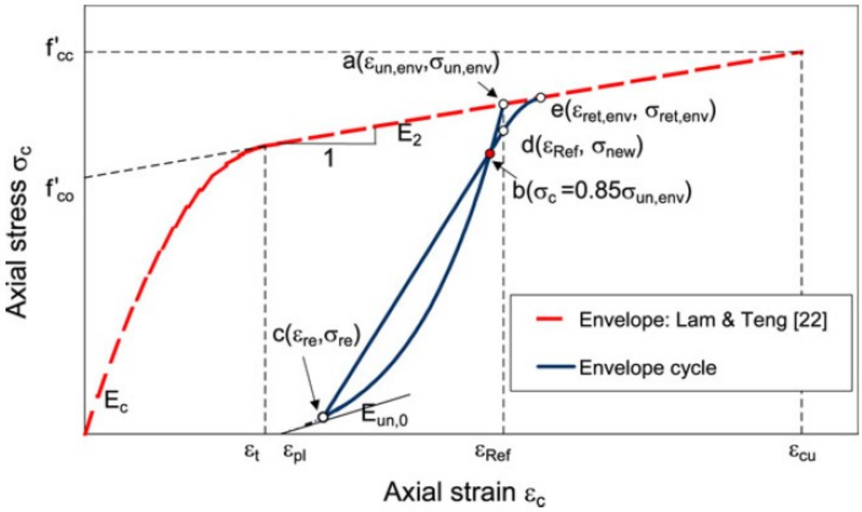

Figure 9. Key parameters of cyclic stress-strain curves of FRP-confined concrete. (Lam and Teng, 2006)

Reloading Curve

The reloading curve consists of linear and parabolic portions. The first one covers from the reloading strain to initial unloading strain and the second one covers from the initial unloading strain to envelop curve.

The linear part is described as below:

$$\sigma_c = \sigma_{re} + E_{re}(\varepsilon_c - \varepsilon_{re}) \qquad (\varepsilon_{re} \le \varepsilon_c \le \varepsilon_{ref}) \tag{29}$$

Where:

$$E_{re} = \frac{\sigma_{new} - \sigma_{re}}{\varepsilon_{ref} - \varepsilon_{re}} \qquad (\varepsilon_{re} \le \varepsilon_c \le \varepsilon_{ref}) \tag{30}$$

The parabolic portion is expressed as follows:

$$\sigma_c = A\varepsilon_c^2 + B\varepsilon_c + C \qquad (\varepsilon_{re} \le \varepsilon_c \le \varepsilon_{ret,env}) \tag{31}$$

where A, B, and C are constants to be resolved. Once An is characterized, constants B and C are given by the accompanying articulations:

$$B = E_{re} - 2A\varepsilon_{ref} \tag{32}$$

$$C = \sigma_{new} - A\varepsilon_{ref}^2 - B\varepsilon_{rf} \tag{33}$$

The plastic strains obtained from the test are presented in comparison with the Lam and Teng model (Lam and Teng, 2006). It is apparent that the plastic strains predicted by Lam and Teng model are overestimated.

2.6 Models of Yankelevsky and Reinhardt

The phenomenological model proposed by Yankelevsky and Reinhardt (1987), shown in Figure 10, describes the unloading and reloading branches, which are submitted as piece-wise linear, while the envelope is assumed to be given. The concept of the model was based on the observable evidence that unloading from the envelope curve exhibits rather high stiffness at low strain reversals, then softens sharply with further unloading.

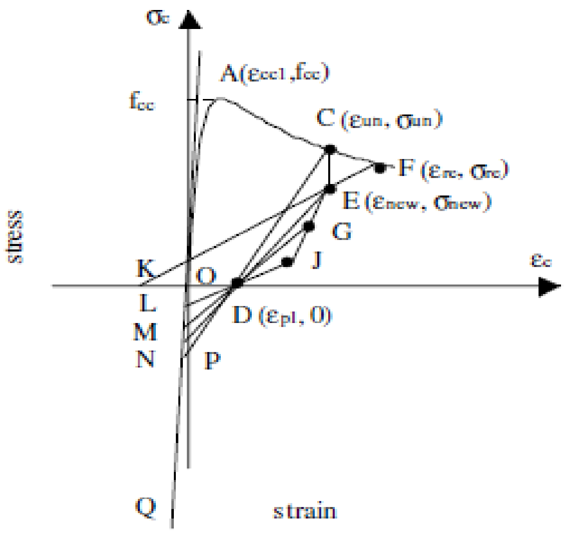

Figure 10. Yankelevsky and Reinhardt model (1987)

Envelope curve:

$$\sigma = fc\left[\frac{2\varepsilon}{\varepsilon_{c1}} - \left(\frac{\varepsilon}{\varepsilon_{c1}}\right)\right] \qquad 0 \le \varepsilon \le \varepsilon_{cc1} \tag{34}$$

$$\sigma = fc\left[1 - \frac{0.5}{\varepsilon_{0.50fc} - \varepsilon_{c1}}(\varepsilon - \varepsilon_{c1})\right] \qquad \varepsilon \ge \varepsilon_{cc1} \tag{35}$$

Unloading Branch:

For $0 \le \varepsilon \le \varepsilon_{cc1}$ a straight line with slope E_c

For $\varepsilon \geq \varepsilon_{cc1}$

The first branch is straight line vertical to the strain axis

The second branch is a straight line with slope $0.50E_cF_c$

Reloading Branch:

For $0 \leq \varepsilon \leq \varepsilon_{cc1}$ a straight line with slope E_c

For $\varepsilon \geq \varepsilon_{cc1}$ a straight line with slope E_cF_c

3. CONCLUSION

In this article six models of Stress-strain for cyclic loading have been reviewed. Some of the models are not entirely original but modified from previous models taking into account some new parameters. So far, these models have been validated experimentally and analytically.

NOTATIONS

E_c: Tangent elasticity modulus of concrete
E_{sec}: Secant elasticity modulus of concrete
n: Material criterion based on the shape of the stress-strain curve
ε_c: Longitudinal compressive concrete strain
ε'_c : Tensile strain
ε_{pl}: Plastic strain
ε_{ro}: Reloading concrete strain
ε_{un}: Unloading concrete strain
σ_c: General concrete stress
σ_f: Crack closure stress
σ_{new}: Deteriorated concrete stress
σ_{ro}: Initial concrete stress on reloading branch
σ_{un}: Reversal envelope stress
f'_c: Compressive strength of concrete
f'_{cc}: Confine concrete compressive strength
ε_{cc}: Compressive strain of longitudinal confined concrete
ε_c: Longitudinal compressive concrete strain
f'_{co}: Compressive strength of unconfined concrete
ε_{co}: Compressive strain of unconfined concrete

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REFERENCES

[1] Aslani, F., & Jowkarmeimandi, R. (2012). Stress-strain model for concrete under cyclic loading. *Magazine of Concrete Research, 64*(8), 673–685. https://doi.org/10.1680/macr.11.00120

[2] Blakeley, R., and Park, R. (1973). Prestressed Concrete Sections with Cyclic Flexure. *ASCE Journal of Structural Division*, *99*(ST8), 1717–1742.

[3] Carneiro, J. A., Lima, P. R. L., Leite, M. B., and Toledo Filho, R. D. (2014). Compressive stress-strain behavior of steel fiber reinforced-recycled aggregate concrete. *Cement and Concrete Composites*, *46*, 65–72.

[4] Carreira, D. J., and Chu, K.-H. (1985). Stress-Strain Relationship for Plain Concrete in Compression. *ACI Journal*, *82*(6), 797–804.

[5] Chen, Y. (2013). Mechanism-Oriented Stress-Strain Model for Unconfined Concrete, ASCE J., 181, 1–37.

[6] Claisse, P., and Dean, C. (2013). Compressive strength of concrete after early loading. *Proceedings of the Institution of Civil Engineers - Construction Materials*, *166*(3), 152–157.

[7] Fatemi, A.A., Tabrizian, Z., Sadeghi, K. (2016), Non-Destructive Static Damage Detection of Structures Using Genetic Algorithm, *International Journal of Civil and Environmental Engineering, 3* (3), 1-5.

[8] Hognestad, E. (1951). A study on combined bending and axial load in reinforced concrete members. *Urbana: Engineering Experimental Station*, *49*(399), 43–46.

[9] Karsan, I. D., and Jirsa, J. O. (1969). Behavior of Concrete under Compressive Loadings. *American Society of Civil Engineers*, *95*(12), 2543–2563.

[10] Kim, J., and Choi, H. (2015). Monotonic Loading Tests of RC Beam-Column Subassemblage Strengthened to Prevent Progressive Collapse. *International Journal of Concrete Structures and Materials*, *9*(4), 401–413.

[11] Konstantinidis, Kappos, and Izzuddin. (2004). Analytical model for unconfined and confined high strength concrete under cyclic loading. *13th World Conference on Earthquake Engineering*, paper no. 2064, Vancouver, Canada.

[12] Kumar, S. (2004). Cyclic Behaviour of Lightly Reinforced Beam-To-Column Joints. *Proceedings of 13th World Conference on Earthquake …*, paper no. 1907. Retrieved from http://www.iitk.ac.in/nicee/wcee/article/13_1907.pdf, Vancouver, Canada

[13] Lam, L., Teng, J. G., Cheung, C. H., & Xiao, Y. (2006). FRP-confined concrete under axial cyclic compression. Cement and Concrete Composites, 28(10), 949-958.

[14] Lam, L., & Teng, J. G. (2009). Stress-strain model for FRP-confined concrete under cyclic axial compression. *Engineering Structures, 31*(2), 308-321.

[15] Liu GT, G. H. and C. F. (2002). *Microstudy on Creep of Concrete at Early Age under Biaxial Compression. Cem Concr Res. 32*:1865-70

[16] Mander, J. B., Priestley, M. J. N., and Park, R. (1989). Theoretical Stress-Strain Model for Confined Concrete. *Journal of Structural Engineering*, *114*(8), 1804–1826.

[17] Massumi, A., Sadeghi, K., Moshtagh, E. (2018), Effects of Deviation in Materials' Strengths on the Lateral Strength and Damage of RC Frames, *Structural Engineering and Mechanics*, *68*(3), 289-297.

ISSN: 2223-9944, e ISSN: 2223-9553

[18] Martin, J. L., David, D., and Terry, R. E. (1991). *Cement Paste, Mortar and Concrete Under Monotonic, Sustained and Cyclic Loading*. KU ScholarWorks.

[19] Martínez-Rueda,J.E. & Elnashai, A.S. Mat. Struct. (1997). Confined concrete model under cyclic load, *Materials and Structures 30*(3), 139–147.

[20] Martinez-Rueda, J. (1997). *Energy dissipation devices for seismic upgrading of RC structures*. Imperial College, Univ. of London. Retrieved from file:///C:/Users/Ali%20King/Downloads/Juan_Enrique_Martinez_Rueda-1997-PhD-Thesis.pdf

[21] Park, R., Kent, D. C., and Sampson, R. A. (1972). Reinforced concrete members with cyclic loading. *Journal of the Structural Division*, *7*(98), 1341–1360.

[22] Popovics, S. (1973). A numerical approach to the complete stress-strain curve of concrete. *Cement and Concrete Research*, *3*(5), 583–599.

[23] Sadeghi, K. (1994). Proposition of a simulation procedure for the non-linear response of R/C columns or piles under oriented lateral loading. *International Journal of Engineering*, *5*(2a), 1–10.

[24] Sadeghi, K. (1995). *Simulation numérique du comportement de poteaux en béton armé sous cisaillementdévié alterné*. Ph.D. Dissertation, Université de Nantes, Nantes, France.

[25] Sadeghi, K. (1998). A New Formulation of Damage Indicator for Structures Subjected to Cyclic and Monotonic Loading, Third International Conference on Coasts, Ports & Marine Structures (ICOPMAS98), Tehran, Iran.

[26] Sadeghi, K. (1998). Proposition of a damage indicator applied on R/C structures subjected to cyclic loading. *Fracture Mechanics of Concrete Structures, 1*, 707-717.

[27] Sadeghi, K. (2001). Proposition of a simulation procedure for the non-linear response of R/C columns under cyclic biaxial bending moment and longitudinal loading. *Proceedings of The First International Conference on Concrete and Development*, *2*, 233–239.

[28] Sadeghi, K. (2002). *Numerical simulation and experimental test of compression confined and unconfined concretes.* Water Resources Management Organization, Ministry of Energy, Concrete Laboratory of Power and Water University of Technology.

[29] Sadeghi, K. (2011). Energy based structural damage index based on nonlinear numerical simulation of structures subjected to oriented lateral cyclic loading. *International Journal of Civil Engineering*, *9*(3), 155–164.

[30] Sadeghi, K. (2014). Analytical stress-strain model and damage index for confined and unconfined concretes to simulate RC structures under cyclic loading, *International Journal of Civil Engineering*, *12*(3), 333-343.

[31] Sadeghi, K. (2015). Nonlinear numerical simulation of RC columns subjected to cyclic oriented lateral force and axial loading. *Structural Engineering and Mechanics, 53*(4), 745-765.

[32] Sadeghi, K. (2017a). Nonlinear Static-Oriented Pushover Analysis of Reinforced Concrete Columns Using Variable Oblique Finite-Element Discretization. *International Journal of Civil Engineering*, *14*(5), 295-306.

[33] Sadeghi, K., Angın, M. (2018). Characteristic Formulas of Damage Indices for

Reinforced Concrete Structures: A General Guideline, *Academic Research International*, *9*(3), 8-18.

[34] Sadeghi, K., Lamirault, J. (1994), A simulation procedure for the nonlinear response of R/C columns under oriented lateral loading, International Symposium of Construction 2000, Romania.

[35] Sadeghi, K., Muhammad, S.M., Sofy, S.A. (2018). Constitutive laws for compression concrete under monotonic and cyclic loading: Characteristic models, *Academic Research International*, *9*(2), 11-23.

[36] Sadeghi, K. (2017b). Nonlinear numerical simulation of reinforced concrete columns under cyclic biaxial bending moment and axial loading. *International Journal of Civil Engineering*, *15*(1), 113-124.

[37] Sadeghi, K., and Nouban, F. (2010a). A New Stress-Strain Law for Confined concrete Under Cyclic Loading. *International Journal of Academic Research*, *2*(4), 6–15.

[38] Sadeghi, K., and Nouban, F. (2010b). A simplified energy based damage index for structures subjected to cyclic loading. *International Journal of Academic Research*, *2*(3), 13-17.

[39] Sadeghi, K., and Sadeghi, A. (2013). Local and microscopic damage indices applicable to RC structures and concretes subjected to cyclic loading. *International Journal of Academic Research*, 5(4), 216-221.

[40] Sadeghi, K., and Nouban, F. (2017a). Behavior modeling and damage quantification of confined concrete under cyclic loading. *Structural Engineering and Mechanics, 61*(5), 625-635.

[41] Sadeghi, K., and Nouban, F. (2017b). Global and Local Cumulative Damage Models for Reinforced Concrete Structures Subjected to Monotonic, Cyclic, or Fatigue Loading. *International Journal of Civil Engineering*, *15*(7), 1063–1075.

[42] Sadeghi, K., and Nouban, F. (2017c). A Highly Accurate Algorithm for Nonlinear Numerical Simulation of RC Columns Under Biaxial Bending Moment and Axial Loading Applying Rotary Oblique Fiber-Element Discretization. *International Journal of Civil Engineering*, *15*(8), 1117–1129.

[43] Sadeghi, K., and Nouban, F. (2016). Damage and fatigue quantification of RC structures. *Structural Engineering and Mechanics, 58*(6), 1021-1044.

[44] Sadeghi, K., and Nouban, F. (2018). An algorithm to simulate the nonlinear behavior of RC 1D structural members under monotonic or cyclic combined loading. *Structural Engineering and Mechanics, 66*(3).

[45] Sadeghi, K., and Nouban, F. (2019). An algorithm for simulation of cyclic eccentrically-loaded RC columns using fixed rectangular finite elements discretization. *Computers and Concrete, 23(1), 25-36.*

[46] Sadeghi, K., Jacques, L., Sieffert J.G. (1993). Proposition de définition d'un indicateur de dommage, Troisième Colloque National de Génie parasismique "Génie parasismique et Aspects vibratoires dans le Génie civil". *AFPS, Volume 2*, Paris.

[47] Hashemi, S. Sh., Sadeghi, K., Vaghefi, M., Seyed A. Siadat (2018). Evaluation of ductility of RC structures constructed with Bubble Deck system. *Structural International Journal of Civil Engineering, 16*(5), 513–526.

[48] Hashemi, S. Sh., Sadeghi, K., Vaghefi, M., Seyed A. Siadat (2020). *Evaluation of the*

response modification factor of reinforced concrete structures using bubble deck slab, Scientia Iranica, Articles in press, Accepted manuscript available online from 7 October 2018.

[49] Spooner, D. C., and Dougill, J. W. (1975). A quantitative assessment of damage sustained in concrete during compressive loading. *Magazine of Concrete Research*, *27*(92), 151–160.

[50] Washa, G. W. and P. G. F. (1950). Effect of Sustained Loading on Compressive Strength and Modulus of Elasticity of Concrete. *Journal of the American Concrete Institute, 46*(No.5, May,), 693–700.

[51] Yankelevsky, D. Z., & Reinhardt, H. W. (1987). Model for cyclic compressive behavior of concrete. *Journal of Structural Engineering, 113*(2), 228-240.

[52] Youssef, M. A., and Moftah, M. (2007). General stress-strain relationship for concrete at elevated temperatures. *Engineering Structures*, *29*(10), 2618–2634.

[53] Zhang, P., Ren, Q., and Lei, D. (2018). Hysteretic model for concrete under cyclic tension and tension-compression reversals. *Engineering Structures*, *163*(August 2017), 388–395

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