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FRP-Steel Relation in Circular Columns to Make an Equal Confinement

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Abstract: In this study FRP-hoop reinforcement relation in circular bridge piers is presented. The ultimate strain criterion is used to obtain an equivalent FRP thickness. Due to multi-parameter effects an explicit relation was not possible. This is then referred to as equivalent FRP thickness. Due to multi parameter effects Artificial Neural Networks (ANN) is used to solve the nonlinear problem. Finite Element Models that were calibrated by previous experimental data provide the input to ANNs. The outputs of ANNs presented reasonable results that were in agreement with real data. The results are displayed in graphs, which can be used to design or rehabilitate existing piers without ever needing to go through FRP codes' design procedures.

Key words: FRP, hoop reinforcement, confinement, finite element, artificial neural networks

INRODUCTION

Earthquakes occurred in current decades have caused great damages to structures, particularly structures that were built according to older codes of practice. Damages and collapses experienced by reinforced concrete structures necessitated repair and retrofitting of these structures. Reinforced concrete bridges also suffered damages such as failure in piers, joints and girders. Piers are the most important structural members in bridges that their failure causes total system to collapse. Because of inadequate transverse reinforcing or short anchorage length in piers, particularly in plastic joint regions, these members fail under low loads. Therefore, retrofitting of bridge piers is inevitable (Solberg *et al*., 2009).

In recent decades, several methods were proposed to improve the flexural capacity and ductility of piers in plastic joint regions. Concrete confinement is a very useful method for ultimate strain enhancement and increasing the compressive strength and energy absorption. In design stage, confinement is provided using closely spaced transverse reinforcements. However, in rehabilitation stage, FRP jacketing is one of the effective methods to compensate the hoop reinforcement deficiencies in piers (Monti *et al*., 2001; Binici, 2007). Therefore, it is desirable to find a relation between the confinement effects produced by FRP and transverse reinforcements. The present study attempts to obtain FRP-hoop reinforcement relation in circular bridge piers. Due to multi-parameter effects, attaining an implicit equation was not possible; thus, Artificial Neural Networks (ANN) was used to determine the relation existed for small experimental specimens. Required data for ANN method were produced using Finite Element Program.

A lot of studies are done about confinement provided by transverse reinforcements and FRP jackets. Early investigators showed that the stress and the corresponding longitudinal strain at the strength of concrete confined by an active hydrostatic fluid pressure can be represented by the following simple relationships (Mander *et al*., 1988):

$$f'_{cc} = f'_{co} + k_1 f_l \quad (1)$$

$$\varepsilon_{cc} = \varepsilon_{co}\left(1 + k_2 \frac{f_l}{f'_{co}}\right) \quad (2)$$

where f'_{cc} and ε_{cc} are the maximum concrete stress and the corresponding strain, respectively under the lateral fluid pressure f_l, f'_{co} and ε_{co} are unconfined concrete strength and corresponding strain, respectively; and k_1 and k_2 are coefficients that are functions of concrete mix and the lateral pressure (Mander *et al*., 1988).

Richart *et al*. (1928) found that the average values of the coefficients for the tests they conducted to be k_1 = 4.1 k_2 = 5 k_1 and also, Balmer (1949) found from his tests that k_1 varied between 4.5 and 7.0 with an average value of 5.6, the higher values occurring at the lower lateral pressures (Mander *et al*., 1988).

Mander *et al*. (1988) presented an equation for confinement produced by transverse reinforcements that then became the base for a lot of models proposed for axial stress-strain curve of concrete confined by FRP jackets. The model presented by Mander *et al*. (1988)

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included members with both circular and rectangular section under uniform and cyclic static and dynamic loading and included any types of steel confinements (Mander *et al*., 1988). Hoshikuma *et al*. (1997) proposed a stress-strain model for concrete including transverse reinforcements confining effects. This model was based on some compressive tests on RC samples. Their test results showed that three parameters: peak stress, strain at peak stress and deterioration rate are important factors in confined concrete stress-strain curve (Hoshikuma *et al*., 1997).

First attempt on using composites for confinement is presented by Fardis and Khalili (1981). They implemented tests on concrete specimens that were confined using fiberglass and proposed a model for concrete stress-strain curve based on Richart model. Samaan *et al*. (1998) proposed a simple and accurate model based on particular expansion property of concrete confined with FRP (Samaan *et al*., 1998).

Li and Sung (2004) studied on shear failure of circular bridge columns retrofitted by FRP jacket presented an effective confined concrete constitutive model named Modified L-L model. It is used for determination of CFRP jacketing effects in retrofitting of bridge piers and to analyze lateral force-displacement relation in circular columns (Perera, 2006). Perera (2006) presented a simplified damage model based on continuum damage mechanics for seismic assessment and retrofit design of columns under flexural-axial combined loading (Hoshikuma *et al*., 1997).

The idea of this study is to use the previously proposed models to establish a relation between required transverse reinforcement and thickness of FRP jackets which is addressed as equivalent FRP thickness. This is done so by finding the FRP thickness that produces the same confinement as a specific reinforcement. Using the equivalent FRP thickness has the advantage of omitting somewhat cumbersome design calculation required by FRP design codes. This way the practicing engineer can design and/or retrofit structural members without extensive knowledge of FRP design procedures. Calculation of equivalent FRP thickness requires solving a multi-parameter nonlinear equation. This is done with the help of Artificial Neural Networks and the results are presented as graphs which can easily be used by designers. The data required for ANNs input are produced using calibrated finite element models. Finally a comparison of the results with real data is presented in the study that shows promising agreement and accuracy.

CONFINING EFFECT IN PIERS

In seismic design of reinforced concrete columns of building and bridge substructures, the potential plastic hinge regions need to be carefully detailed for ductility in order to ensure that the shaking from large earthquakes will not result in a collapse. Adequate ductility of members of reinforced concrete frames is also necessary to ensure that moment redistribution can occur. The most important design consideration for ductility in plastic hinge regions of reinforced concrete columns is the provision of sufficient transverse reinforcement in the form of spirals or circular hoops or of rectangular arrangements of steel, in order to confine the compressed concrete, to prevent buckling of the longitudinal bars and to prevent shear failure. Anchorage failure of all reinforcement must also be prevented (Mander *et al*., 1988).

Confinement can be achieved by steel jacketing. Steel tubes filled with concrete have important benefits. Their benefits include high stiffness and strength, large energy absorption and enhanced ductility and stability. The tube interacts with the core in three ways: (1) it confines the core, thereby enhancing on its compressive strength and ductility; (2) it provides additional shear strength for the core and (3) depending on its bond strength with concrete and its stiffness in axial direction, it develops some level of composite action, thereby also enhancing the flexural strength of concrete. The core, in return, prevents buckling of the tube. Since steel is an isotropic material, its resistance in axial and transverse direction can be neither uncoupled nor optimized. Also, its high modulus of elasticity causes a large portion of axial loads to be carried by the tube, resulting in premature buckling. Furthermore, its Poisson's ratio is higher than of concrete at early stages of loading (Fardis and Khalili, 1981). This differential expansion results in partial separation of two materials, delaying the activation of confinement mechanism. Finally, outdoor use of steel tubes in corrosive environments may prove costly (Mirmiran and Shahawy, 1997).

Using Fiber Reinforced Plastic (FRP) materials may eliminate these problems. Hybrid construction with FRP and concrete combines the mass, stiffness, damping and low cost of concrete with the speed of construction, lightweight, strength and durability of FRPs. The orthotropic behavior of FRPs makes them most suitable for encasing concrete columns. FRP jackets have already been successfully used in the field of retrofitting of concrete columns (Saadatmanesh *et al*., 1994).

FRP-HOOP RELATION IN CIRCULAR COLUMNS

For clarity, it is needed to present a definition of equal confinement. If axial stress-strain curve of concrete confined with hoop reinforcement coincide with stress-strain curve of concrete confined with FRP, it can be said that hoop reinforcements and FRP have an equal confinement effect on concrete. However, it is clear that because of differences in FRP and steel properties, this condition occurrence is not possible. Therefore, it is necessary to consider an equal confinement criterion. Usually in columns under axial compressive load, if concrete strain reaches to ultimate strain, columns failure will be inevitable. Thus, in the present study, equal ultimate strain in concrete was considered as an equal confinement criterion in both columns confined with FRP or hoop reinforcements. On the other hand, if ultimate strain in concrete confined with hoop is equal to ultimate strain in concrete confined with FRP, it can be said that confinement is equal. Attaining to FRP-hoop reinforcement relation some data was produced in finite element program.

Data production in finite element program: In the present study, Finite Element Program (FEP) was used to produce data needed to find FRP-hoop relation using Artificial Neural Network. However, it is always necessary to verify a finite element model. For this, an experimental specimen tested by Hoshikuma *et al.* (1997) was used for concrete confined with transverse reinforcements and sample tested by Samaan *et al.* (1998) was used for concrete confined by FRP.

The specimen tested by Hoshikuma *et al.* (1997) was 1500 mm in height and 500 mm diameter. Other specimen properties are presented in Table 1.

Concrete and reinforcements stress-strain curves were assumed as multi-linear and kinematic bilinear, respectively. A 3D finite element model meshed by tetrahedron shaped elements was used for simulation. The pier was fixed at the lower end and the load was applied by displacement control method. The model geometry is shown in Fig. 1.

Specimen was subjected to a uniform compressive load and analyzed statically. Axial stress and strain distribution of modeled sample is shown in Fig. 2. In order to perform buckling control, the model was once analyzed for buckling using the Eigen buckling command.

In Fig. 3, Stress-strain curves obtained from finite element modeling and relations presented by Mander *et al.* (1988) and Hoshikuma *et al.* (1997) are

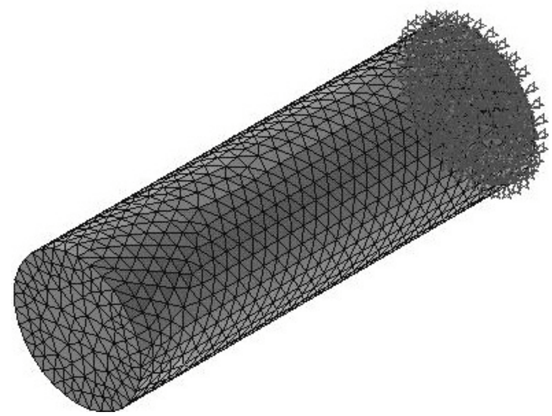

Fig. 1: Modeled column geometry

Table 1: Properties of RC Column specimen tested by Hoshikuma *et al.* (1997)

Properties	Values
Concrete compressive strength (Mpa)	28.8
Steel yield strength (Mpa)	295.0
Concrete modulus of elasticity (Mpa)	20000.0
Hoops volumetric ratio (%)	0.39
Concrete Poisson ratio	0.2
Reinforcement's volumetric ratio (%)	1.01
Steel Poisson ratio	0.3
Hoop diameter (mm)	10.0
Steel modulus of elasticity (Mpa)	210000.0
Hoops space (mm)	150.0

shown. It can be seen that stress obtained from FEP for an equal strain is greater than experimental curves. Also, an ultimate strain in FEP is less than that of experimental models.

Similarly, the result of FEP should be validated for RC columns confined with FRP jacket. For this, a column tested by Samaan *et al.* (1998) was modeled. The sample has a height 305 mm and a diameter 152.5 mm that is confined with GFRP tube and was subjected to axial compressive load. Other properties of a sample are given in Table 2.

FRP behavior was considered perfectly elastic and Tsai-Wu criterion was used as failure criterion. After analyzing of a sample, axial stress-strain curve was obtained as follows (Fig. 4). It can be seen that similar to concrete confined with hoops, stress obtained from FEP curve for an equal strain is greater than experimental curves. Also, ultimate strain in FEP is less than that of experimental models.

The result of both models, confined with transverse reinforcements and FRP jacket, are similar in comparison with experimental results. Also, in stress-strain curves

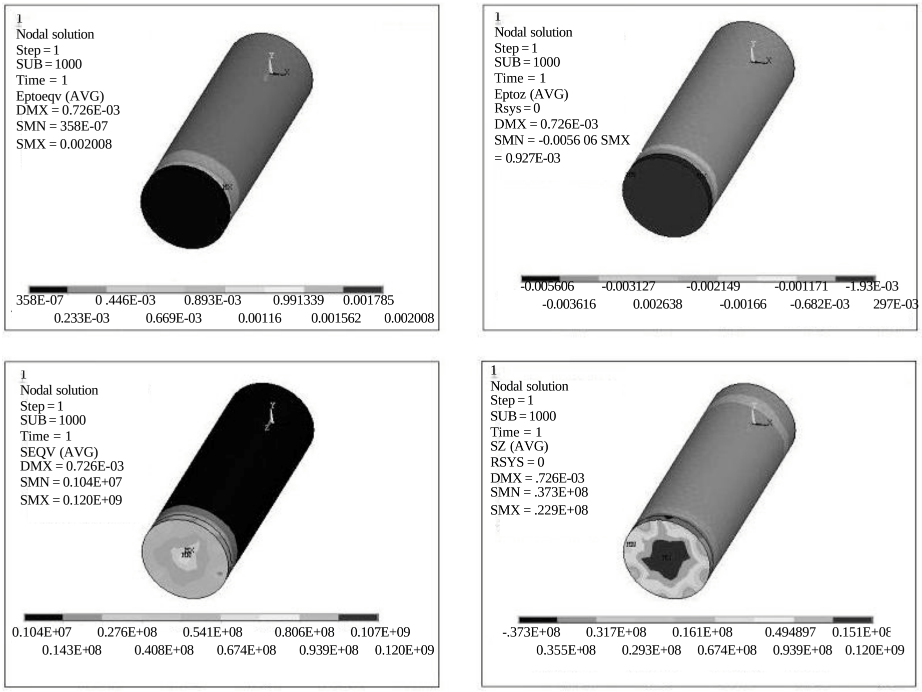

Fig. 2: Axial stress and strain distribution

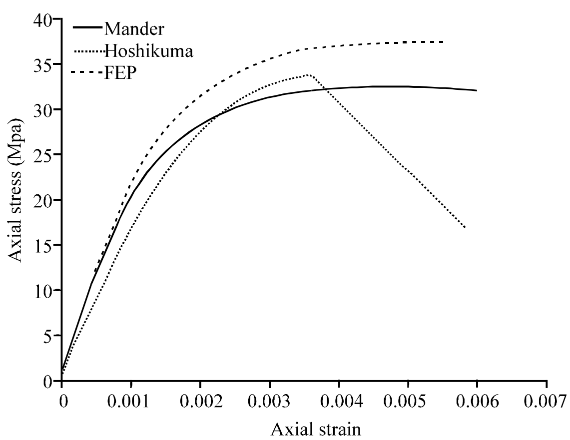

Fig. 3: Axial stress-strain curves of RC column confined with hoop confinements

Table 2: Properties of concrete and GFRP in a sample tested by Samaan *et al*. (1998)

Properties	Values
No. of GFRP layers	10.00
GFRP tensile strength(Mpa)	2186.00
Concrete modulus of elasticity (Mpa)	20000.00
GFRP modulus of elasticity (Mpa)	69640.00
Concrete Poison's ratio	0.20
GFRP shear modulus (Mpa)	30130.00
Concrete compressive strength (Mpa)	30.86
Thickness of GFRP per layer (mm)	0.20
GFRP Poison's ratio	0.22

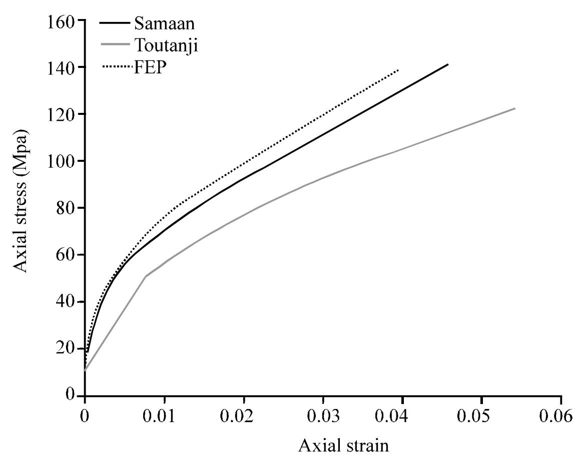

Fig. 4: Axial stress-strain curves of RC column confined with FRP

given by Mirmiran *et al.* (2000) the same conditions (smaller ultimate strain and higher stress) are seen (Fig. 5).

While, the main objective of this present study is comparison of FRP confined columns with hoop confined columns to obtain the FRP- hoop relation and because of fairly accurate results from FEM, it can be concluded that FEP outputs are correct to extract FRP-hoop relation in small columns.

FEP analyses is based on Finite Element Method. In FEPs, three types of equations are used and solved: equilibrium, consistency and boundary equations. These are fundamentals of any models solution. Therefore, it can be concluded that FEP outputs are valid for columns modeled with any sizes.

After validation of FEP, it was used to create data for ANN. In order to produce each data, two columns with same dimensions and concrete material, one confined with hoop and another confined by FRP jacket, were modeled in FEP. At first, reinforced concrete column was analyzed with a small number of steps and the ultimate strain of concrete is determined at the point of rupture. Then, concrete column confined with FRP was analyzed with a small number of steps. In this stage, tensile strength and FRP modulus of elasticity are given and only its thickness is changed to obtain to the ultimate strain of concrete equal or near to that of reinforced concrete column. Finally, both columns were analyzed with small step intervals to achieve the desired accuracy. In this stage, if the concrete ultimate strain is not equal in columns, the model was changed until equal concrete ultimate strain in both models is reached.

In total, 122 data were created in this way. Table 3 shows several data that were made using FEP.

Regression analysis: The data produced by FEP are plotted in Fig. 6. In Fig. 6 steel reinforcement and FRP volumetric ratio are plotted against each other and each data represents the two FEP models that have reached a similar ultimate strain and thus showing the FRP amount that has an equal effect as steel reinforcement.

It is clear that no explicit trend or relationship exists that describes variations of FRP thickness with respect to transverse reinforcements.

Proposed equation based on experimental models: In this section in order to find a relation between FRP thickness and transverse reinforcement, models proposed based on experiments are used to define and parameterize the problem.

A concrete axial stress-strain model considered by Hoshikuma *et al.* (1997) included two branches (ascending and falling branches). Equation for ascending branch was given as:

$$f_c = E_c \varepsilon_c [1 - \frac{1}{n}(\frac{\varepsilon_c}{\varepsilon_{cc}})^{n-1}] \quad (3)$$

$$n = \frac{E_c \varepsilon_{cc}}{E_c \varepsilon_{cc} - f_{cc}} \quad (4)$$

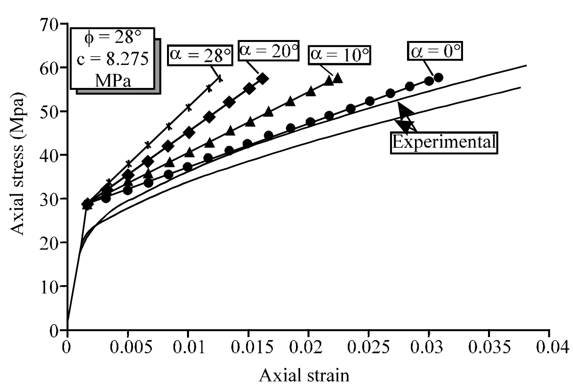

Fig. 5: Stress-strain curves given from FEP in comparison with experimental curves (Mirmiran *et al*., 2000)

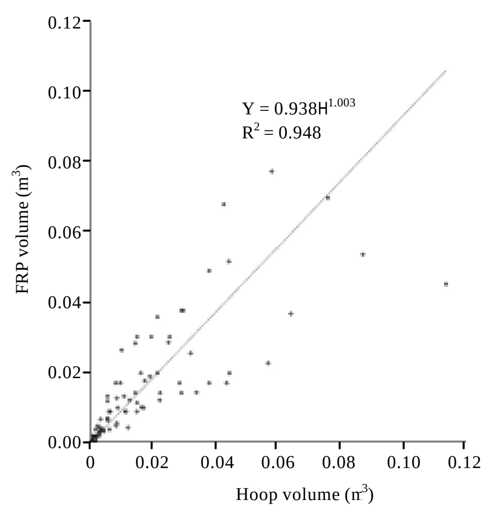

Fig. 6: FRP-hoop equation from regression analysis

Table 3: Several data made with FEP

Column diameter (mm)	Column height (mm)	Concrete strength (MPa)	Hoop diameter (mm)	Hoop spacing (mm)	Hoop yield strength (MPa)	FRP tension strength (MPa)	FRP modulus of elasticity (MPa)	FRP thickness (mm)
100	200	30.2	10	100	300	700	18000	1.1
152	610	26.22	6	100	350	500	17000	0.3
700	2400	25.00	12	150	250	600	18000	0.7
500	1500	28.80	10	100	400	600	36000	0.8
1500	6000	40.00	14	100	300	900	69000	0.6

where f_{cc}, ε_{cc} and are peak stress, strain at peak stress and initial stiffness, respectively. ε_{cc} and f_{cc} for circular columns were presented as:

$$f_{cc} = f'_{co}(1 + 3.83\frac{\rho_s f_{yh}}{f_{co}}) \quad (5)$$

$$\varepsilon_{cc} = 0.00218 + 0.0332\frac{\rho_s f_{yh}}{f_{co}} \quad (6)$$

In above equations ρ_s, f_{yh}, f_{co} are hoop volumetric ratio, hoop yield stress and plane concrete compressive strength, respectively. Falling branch equation was presented as follows:

$$f_c = f_{cc} - E_{des}(\varepsilon_c - \varepsilon_{cc}) \quad (7)$$

$$E_{des} = 11.2\frac{f_{co}^2}{\rho_s f_{yh}} \quad (8)$$

where, E_{des} is the deterioration rate which is developed from regression analysis of test data in the range ε_c to ε_{cu}. The definition of ultimate strain (ε_{cu}) is important. In the tests, crushing of core content and buckling of longitudinal reinforcement were observed when the compressive stress dropped to less than 0.5 f_{cc}. Because such damage is excessive and not repairable, the strain corresponding to 50% of the peak stress f_{cc} is assumed as the ultimate strainand obtained as (Hoshikuma *et al*., 1997):

$$\varepsilon_{cu} = \varepsilon_{cc} + \frac{f_{cc}}{2E_{des}} \quad (9)$$

In Hoshikuma *et al*. (1997) model, substituting Eq. 5, 6 and 8 in Eq. 9, it will be as follows:

$$\varepsilon_{cu} = \varepsilon_{u_s} = 0.00218 + 0.0332\frac{\rho_s f_{yh}}{f'_{co}} + \frac{f'_{co}(1 + 3.83\frac{\rho_s f_{yh}}{f'_{co}})}{2\times 11.2\frac{f'^{\,2}_{co}}{\rho_s f_{yh}}} \quad (10)$$

Samaan *et al*. (1998) presented a bilinear model for concrete confined by FRP. Richard and Abbott (1975) presented it as a four-parameter equation and calibrated it as:

$$f_c = \frac{(E_1 - E_2)\varepsilon_c}{[1 + (\frac{(E_1 - E_2)\varepsilon_c}{f_o})^n]^{1/n}} + E_2\varepsilon_c \quad (11)$$

where, f_c and ε_c are axial stress and strain in confined concrete, respectively; E_1 and E_2 are initial and secondary slopes, respectively; f_o is the reference plastic stress at the interception of the second slope with the stress axis; and n a curve-shape parameter that mainly controls the curvature in the transition zone. It can be shown that the model is not very sensitive to the curve-shape parameter n and a constant value of 1.5 was used. The first slope (E_1) depends solely on concrete and to evaluate it, the following formula for the secant modulus as proposed by Ahmad and Shah (1982) was adopted (Samaan *et al*., 1998):

$$E_1 = 3950\sqrt{f'_c} \quad (12)$$

The second slope (E_2) is a function of the stiffness of the confining tube and to a lesser extent, the unconfined strength of concrete core, as follows:

$$E_2 = 245.61f'^{\,0.2}_c + 1.3456\frac{E_j t_j}{D} \quad (13)$$

In above equations f'_c is unconfined concrete strength (MPa), E_j effective modulus of elasticity of the tube in the hoop direction and the interception stress f_o is a function of the strength of unconfined concrete and the confining pressure provided by the tube and was estimated as:

$$f_0 = 0.872f'_c + 0.371f_r + 6.258 \quad (14)$$

f_r is the confinement pressure as given by:

$$f_r = \frac{2f_j t_j}{D} \quad (15)$$

where, f_j = hoop strength of the tube; and D = core diameter:

Samaan *et al*. (1998) estimated peak stress and strain of concrete confined with FRP tube as follows:

$$f'_{cu} = f'_c + 6f_r^{0.7} \quad (16)$$

$$\varepsilon_{cu} = \frac{f'_{cu} - f_o}{E_2} \quad (17)$$

Substituting Eq. 13, 14 and 16 in Eq. 16, it will be as:

$$\varepsilon_{cu} = \varepsilon_{u_f} = \frac{f'_{co} + 6(\frac{2f_j t_j}{D})^{0.7} - 0.872f'_{co} - 0.371\frac{2f_j t_j}{D} - 6.258}{245.61f'^{\,0.2}_{co} + 1.3456\frac{E_j t_j}{D}} \quad (18)$$

Now, if equal ultimate strain in concrete is considered as an equal confinement criterion, equating Eq. 10 and 18:

$$0.00218+0.0332\frac{\rho_s f_{yh}}{f'_{co}}+\frac{f'_{co}(1+3.83\frac{\rho_s f_{yh}}{f'_{co}})}{2\times 11.2\frac{f'^{2}_{co}}{\rho_s f_{yh}}} = \frac{f'_{co}+6(\frac{2f_j t_j}{D})^{0.7}-0.872f'_{co}-0.371\frac{2f_j t_j}{D}-6.258}{245.61f'^{0.2}_{co}+1.3456\frac{E_j t_j}{D}} \quad (19)$$

It should be noted that the above equation is valid only for test specimens with small sizes. But two points are derived from above equation:

- It is found that there are 8 parameters affecting FRR-hoop relation that are: column height (H), column diameter (D), hoop diameter (d), hoop spacing (s), FRP yield strength (f_j), FRP modulus of elasticity (E_j), compressive strength of concrete (f'_{co}) and hoop yield strength (f_y). FRP thickness (t_j) is considered as a parameter that its relation with hoop needs be obtained
- Equation 19 can be modified to use for tall columns. Thus a correction coefficient K was added to the right hand side of the equilibrium to account for the difference. Therefore, Eq. 19 takes the form below:

$$\varepsilon_{u_w} = k\times\varepsilon_{u_f}$$

$$0.00218+0.0332\frac{\rho_s f_{yh}}{f'_{co}}+\frac{f'_{co}(1+3.83\frac{\rho_s f_{yh}}{f'_{co}})}{2\times 11.2\frac{f'^{2}_{co}}{\rho_s f_{yh}}} = k\times\frac{f'_{co}+6(\frac{2f_j t_j}{D})^{0.7}-0.872f'_{co}+0.371\frac{2f_j t_j}{D}+6.258}{245.61f'^{0.2}_{co}+1.3456\frac{E_j t_j}{D}} \quad (20)$$

Once the coefficient K is determined, the equivalent FRP thickness (t_j) can be calculated by Eq. 20. ANN was used to derive a relationship between K and the rest of the parameters, which are discussed in the following.

DETERMINATION OF COEFFICIENT K

Determination of K coefficient was implemented by using ANN and the produced data in FEP were used to train the network. Usually, ANN methods consist of two steps: 1-traininig 2- testing. In training step, 100 produced data consisting of 8 inputs and 1 output was applied to ANN. 22 remaining data were also applied in the testing step. If ANN outputs correspond to real outputs, it can be said that ANN can predict FRP-hoop relation correctively.

Figure 7 shows ANN outputs in comparison with available data for training and testing steps, respectively. It is clear that ANN outputs for small amount of FRP volume are not predicted very well. Therefore, in spite of good correlation coefficient, ANN outputs are not valid.

There are two methods to solve this problem: (1) normalization of data (2) increase of data. If ANN outputs are not improved with data normalizing, increase of data is inevitable.

Figure 8 shows ANN normalized outputs in comparison with FEP data that were normalized in range of 0.1 to 1 and applied to ANN. It can be seen that data normalization is an effective method and ANN to FEP output ratios are better than that of un-normalized data. Therefore, application of normalized data to ANN, results in better prediction of outputs. On the other hand, ANN is only valid for normalized data in range of 0.1 to 1.

Now, ANN can be used to determine K coefficient. For this, each of 8 effective parameters was considered as a constant and the other 7 parameters were changed to obtain a relation between K and the constant parameters. However, it did not lead to best results. Then, two parameters of 8 effective parameters were considered as constants and other 6 parameters were changed. It was found that if concrete compressive strength (f'_c) and steel yield strength (f_y) was considered as constant parameters, curves as follow can be obtain for $\sqrt{\varepsilon_{u_w}}$ versus $K/\sqrt{\varepsilon_{u_w}}$. Similar graphs can be plotted for different values of f'_c and f_y. Figure 9 only shows results for four different pairs.

For example, considering a reinforced concrete column with the parameters: height 5000 mm, diameter 1000 mm, concrete strength 50 MPa, reinforcement ratio 0.004, steel yield stress 325 MPa; using Eq. 10 the ultimate strain is estimated as follows:

$$\varepsilon_{u_w} = 0.00218+0.0332\frac{\rho_s f_{yh}}{f'_{co}}+\frac{f'_{co}(1+3.83\frac{\rho_s f_{yh}}{f'_{co}})}{2\times 11.2\frac{f'^{2}_{co}}{\rho_s f_{yh}}}$$

$$\varepsilon_{u_w} = 0.00218+0.0332\frac{0.004\times 325}{30}+\frac{(30+3.83\times 0.004\times 325)}{2\times 11.2\frac{30^2}{0.004\times 325}} = 5.976\times 10^{-3}$$

$$\sqrt{\varepsilon_{u_w}} = 0.0773 \rightarrow$$

Using graphs for f'_{co} = 30 MPa, f_y = 325 MPa (Fig. 9):

$$\frac{K}{\sqrt{\varepsilon_{u_w}}} = 9.8 \rightarrow \quad K = 9.8\times 0.0773 = 0.75754$$

Now using a GFRP of tensile strength 800 MPa and modulus of elasticity 30000 MPa the equivalent FRP thickness is calculated from Eq. 20:

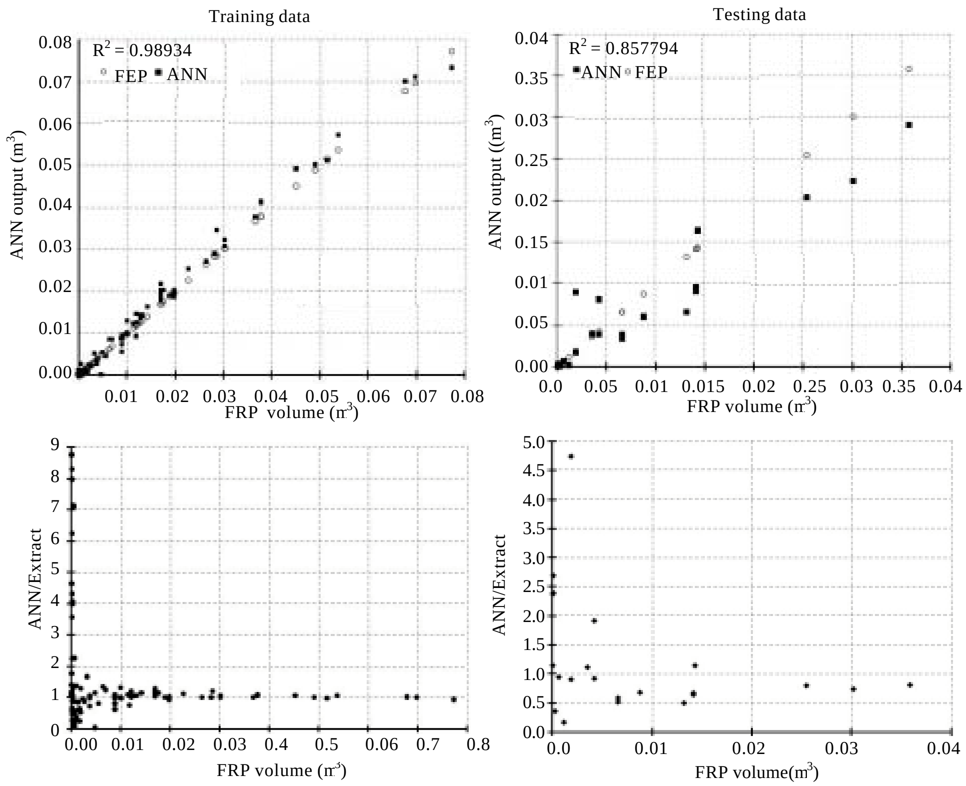

Fig. 7: ANN outputs in comparison with available data for training and testing steps

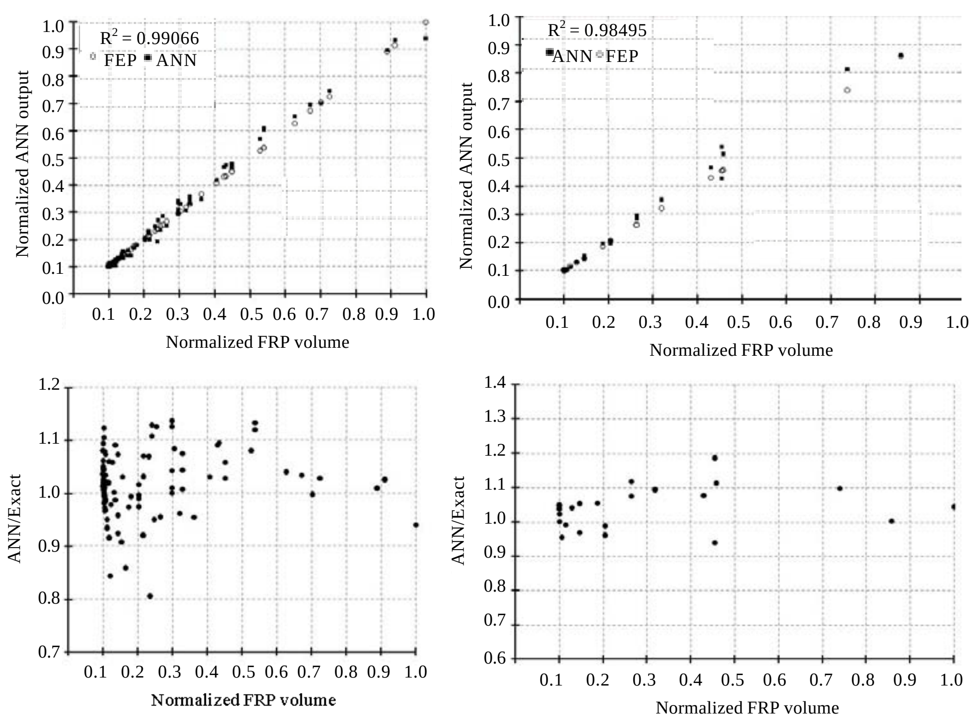

Fig. 8: ANN normalized outputs in comparison with available normalized data for training and testing steps

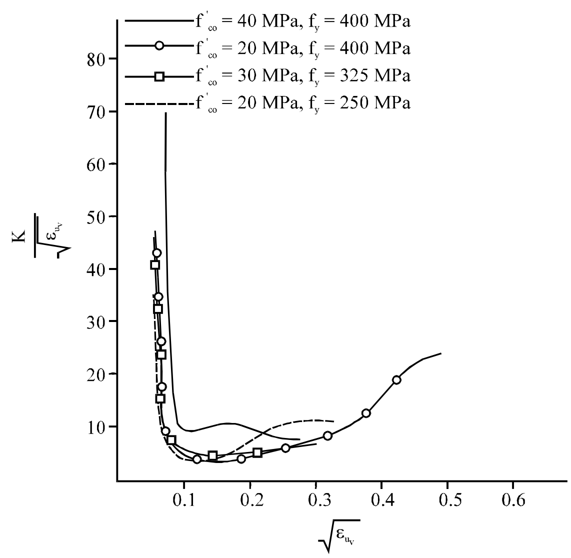

Fig. 9: $\sqrt{\varepsilon_{u_\psi}}$ versus $\frac{K}{\sqrt{\varepsilon_{u_\psi}}}$ curves

$$\varepsilon_{u_\psi} = 5.976\times10^{-3}$$

$$= 0.8237\times\frac{30+6(\frac{2\times800t_j}{1000})^{0.7}-0.872\times30+0.371\frac{2\times800t_j}{1000}+6.258}{245.61\times30^{0.2}+1.3456\frac{30000t_j}{1000}}$$

Solution of the above equation results in an equivalent FRP thickness of 0.77 mm. This is the thickness that if used, results in the same ultimate strain as when transverse reinforcement is present. If according to a code of practice (perhaps a newer code) this column would require more reinforcement to ensure required performance, then the equivalent FRP thickness can be calculated in the same way. The difference between the two thicknesses is the thickness of FRP material needed to retrofit the pier.

CONCLUSION

In recent decades, several methods were proposed to improve the flexural capacity and ductility of piers in plastic joint regions. Concrete confinement is a very useful method for fracture strain enhancing and increasing in compressive strength and energy absorption. In design stage, confinement is provided using closely spaced transverse reinforcements. In retrofitting of concrete structures, particularly bridges, one of effective methods to compensate for hoop reinforcements in piers is FRP jacketing. Using a relation between FRP and transverse reinforcements, FRP amount to compensate for hoop reinforcements deficiency can be obtained. In the present study, FRP-hoop reinforcement equation in circular bridge piers was derived from existing experimental models. Because of multi-parameter effects, an explicit relation was not possible, therefore Artificial Neural Network (ANN) was used to popularize the equation existed for experimental models. Required data for ANN were produced using FEP. It was found that if concrete compressive strength (f'_c) and steel yield strength (f_y) were considered as constants, a relation between $\sqrt{\varepsilon_{u_\psi}}$ and $K/\sqrt{\varepsilon_{u_\psi}}$ is possible. Comparison of FEP created data with results obtained from proposed equation and plotted graphs, good agreements between experimental results and the proposed were observed. In this way equivalent FRP thickness corresponding to hoop reinforcements can be calculated and used for design and retrofitting of structures.

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