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A COMPARATIVE STUDY ON COMPRESSIVE BEHAVIOR OF H.S. STEEL VS. FRP CONFINED CONCRETE

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ABSTRACT
This paper presents the results of an experimental and analytical study on application of “high strength steel strapping” technique and comparing it with FRP for retrofit of concrete columns. Various parameters were found to influence the compressive strength and ductility of confined concrete, including confinement mechanical volumetric ratio, number of confinement layers, strength of plain concrete and ductility of confining material. Among these parameters, the latter was found to play the most important role in determining the ultimate strain and post peak behavior of concrete. Axial compressive tests were performed on small-scale circular or square section concrete columns. Three different materials were applied for confining concrete specimens, including CFRP jacket, brittle high-strength steel strips and ductile steel strip. Test Results showed significant increase in strength and ductility of columns due to active confinement by metal strips. CFRP confined concrete also showed enhanced behavior. A database of results of compressive tests on concrete confined with various materials was collected from the literature. An analytical model was proposed based on results of this study and the collected database to determine the strength and ultimate strain of confined concrete. The proposed model takes the confinement ductility into account and shows good agreement with the experimental results.

Keywords: concrete, confinement, FRP, steel strip, ultimate strain

1. INTRODUCTION
It is well known and proven that lateral confinement improves the strength and ductility of concrete. Confinement reinforcement is generally applied to compressive members as lateral reinforcement with the aim of increasing their load carrying capacity and their ductility in case of seismic upgrading. In addition, lateral confinement prevents slippage and buckling of the longitudinal reinforcement (Saadatmanesh et al., 1994). Lateral reinforcement can be provided by using circular hoops, rectangular ties, jacketing by steel, FRP, ferrocement, etc.
Since many of the existing RC columns are vulnerable under severe earthquakes due to low ductility, increasing the concrete compressive displacement capacity by confinement becomes a vital issue. Several researches have been conducted in the field of strength and ductility enhancement of concrete by confinement with various materials.

In addition, various models have been proposed for approximating the gain in strength, peak strain and ultimate strain due to confinement. Since the confinement ductility has not been considered as a parameter of study, in almost all of the existing experiments and models, the effect of ductility of confining material on ductility enhancement of concrete has been missed. This paper presents the results of an experimental and analytical study that focuses on this issue. This study was part of a comprehensive investigation on different techniques of concrete retrofit. The study included axial compressive tests on concrete specimens with square or circular sections with or without internal confining bars that were retrofitted with two types of metal strips as well as CFRP jackets.

Confinement models for peak of the compressive behavior a review of the available confining models in the literature shows that almost all of the existing confinement models include an identical form in which strength of confined concrete and the corresponding peak strain is a function of effective lateral pressure f_{le} and strength of plain concrete f'_c as rewritten in Table 1. One of the main differences of these models is the assumed parameters or approaches in computing the effective lateral pressure. Some models use the yield force of confining material for computing the lateral pressure, while a few of these models try to obtain the existing stress in the confining material at the peak axial stress. However, this issue is more important for estimating the strength of steel-confined concrete.

In addition, in some models, the lateral pressure is decreased to account for the ineffectively confined zones of concrete columns which was firstly introduced by Sheikh and Uzumeri 1982 and by Mander et al. 1984 and then applied in EC8. Therefore, according to the most advanced confinement models, the effective lateral pressure is a function of mechanical volumetric ratio of confining material and geometry and dimensions of concrete column and its longitudinal and transverse reinforcements.

Confinement Models for Ultimate Compressive Strain

In contrast to the peak point in stress-strain behavior of concrete, ultimate compressive strain has not been consistently defined with various researchers. In contrast to the tensile tests, in which an apparent rupture could be observed, the definition of the ultimate point in compressive tests of concrete is a controversial issue. For steel-confined concrete, CEB model code 90 (1993) uses the strains on the post-peak branches of stress-strain curves of confined and unconfined concretes that corresponds to a stress level of 85% of strength of unconfined concrete as the ultimate strain of confined and unconfined concretes, respectively.

Cusson and Paultre (1995) used the strains at which the stress drops to 50% of corresponding strengths of confined or unconfined concrete as the ultimate strains of confined or unconfined concretes, respectively. Razvi and Saatcioglu 1999 used an approach similar to that of Cusson and Paultre 1995, in which strains at 85% of strength of confined and unconfined concretes are applied as the ultimate strains of confined and unconfined concretes, respectively. It is observed that there is much difference between theses measures.

However, for FRP confined concrete an obvious ultimate point can be observed which corresponds to the rupture of FRP jacket. Lam and Teng 2003

Table 1: A Summary of Famous Steel-Based Confinement Models

Model	Confined concrete strength	Strain at peak stress
Richart 1928	$f'_{cc} = f'_{co}[1 + 4.1 f_{le}]$	
Newman 1971	$f'_{cc} = f'_{co}\left[1 + 3.7\left(\frac{f_{le}}{f'_{co}}\right)^{0.86}\right]$	
Sheikh and Uzumeri 1982	$f'_{cc} = Kf'_{co}$ $K = 1.0 + \frac{b_c^2}{140P_{acc}}\left[\left(1 - \frac{ns_l^2}{5.5b_c^2}\right)\left(1 - \frac{s}{2b_c}\right)^2\right]\sqrt{\rho_s f_{sh}}$	$\varepsilon_{cc} = 80Kf'_c \times 10^{-6}$
Park 1982	$f'_{cc} = f'_{co}(1 + 2\frac{f_l}{f'_c})$	$\varepsilon_{cc} = \varepsilon_{co}(1 + 2\frac{f_l}{f'_c})$
Fafitis and Shah 1985	$f'_{cc} = f'_{co} + (1.15 + \frac{3048}{f'_c}) f_l$	
Saatcioglu and Razvi 1992	$f'_{cc} = f'_{co} + 6.7(f_{le})^{0.83}$	$\varepsilon_{cc} = \varepsilon_{co}(1 + 33.5\left(\frac{f_{le}}{f'_{co}}\right)^{0.83}$
Ahmad & Shah 1982	$f'_{cc} = f'_{co}\left[1 + 4.2556\left(\frac{f_l}{f'_{co}}\right)\right] \quad if \ \frac{fl}{f'_{co}} < 0.68$ $f'_{cc} = f'_{co}\left[1.7757 + 3.1171\left(\frac{f_l}{f'_{co}}\right)\right] \quad if \ \frac{fl}{f'_{co}} > 0.68$	
Mander et al 1988	$f'_{cc} = f'_{co}\left[2.254\sqrt{1 + 7.94\frac{fl}{f'_{co}}} - 2\frac{fl}{f'_{co}} - 1.254\right]$	$\varepsilon_{cc} = \varepsilon_{c0}\left[1 + R\left(\frac{f_{cc}}{f_{c0}} - 1\right)\right]$
Karabinis 1994	$f'_{cc} = f'_{co} + 4.269 f_l^{0.587}$	
Hoshikuma et al. (1997)	$f'_{cc} = f'_{co}(1 + 7.6\frac{f_{ley}}{f_{co}})$	
Cusson & Paultre 1995	$f'_{cc} = f'_{co}(1 + 2.1(\frac{f_{ley}}{f'_{co}})^{0.7})$	$\varepsilon_{cc} - \varepsilon_{co} = 0,21\left(\frac{f_{le}}{f_{co}}\right)^{1,7}$
EC8 2001	$f'_{cc} = f'_{co}(1 + 5(\frac{f_{ley}}{f'_{co}})) \quad \alpha\omega_w \leq 0.1$ $f'_{cc} = f'_{co}(1.125 + 2.5(\frac{f_{ley}}{f'_{co}})) \quad \alpha\omega_w \geq 0.1$	$\varepsilon_{cc} = \varepsilon_{co}(1+2.5\,\alpha\omega_w)^2$ $\varepsilon_{cc} = \varepsilon_{co}(1.125+1.25\alpha\omega_w)^2$

Table 2: Models for ultimate compressive strain of concrete

Model	Ultimate strain of confined concrete
CEB model code 90 (1993)	$\varepsilon_{85C} = \varepsilon_{85U} + 0.1\left(\frac{f_{le}}{f'_{co}}\right)$
Cusson and Paultre (1995)	$\varepsilon_{50C} = \varepsilon_{50U} + 0.15\left(\frac{f_{le}}{f'_{co}}\right)$
Seible et al. (1995)	$\varepsilon_{cu} = 0.004 + 1.4\left(\frac{f_{le}}{f'_{cc}}\varepsilon_{ju}\right)$ steel $\quad \varepsilon_{cu} = 0.004 + 2.65\left(\frac{f_{le}}{f'_{cc}}\varepsilon_{ju}\right)$ FRP
Cusson and Paultre (1995)	$\varepsilon_{50C} = \varepsilon_{50U} + 0.15\left(\frac{f_{le}}{f'_{co}}\right)$
Razvi and Saatcioglu (1999)	$\varepsilon_{85C} = \varepsilon_{85U} + 260k_3\rho\varepsilon_{cc}[1 + 0.5k_2(k_4 - 1)]$

2. EXPERIMENTAL PROGRAM

This paper presents parts of the results of a comprehensive study on application of the strapping technique for concrete strengthening. The Experiments presented in this paper included axial compressive tests on 30 prismatic 15*30 concrete columns. The axial and lateral stress-strain behaviors of concrete specimens were obtained by simultaneously measuring the force and axial and lateral displacements of specimens. Several parameters were considered for column specimens and retrofitting including compressive strength of concrete, yield strength, ductility, spacing and size of confining strips. A detailed description of the results of strapped concrete columns with various shapes and sizes has been presented by the authors [13], in which several other parameters affecting the response of strapped concrete is discussed in detail. But the main aim of this paper is studying the effect of mechanical properties of confining material on behavior of confined concrete. Three different materials were used for confining concrete columns, including two different types of strips that are called S and T types, as well as CFRP.

Prismatic specimens were fabricated in the structure and concrete Laboratory at the building and housing research center. Three different concrete mixtures were used to study the effect of strength of plain concrete on response of confined concrete as listed in Table 3. The first set (B1) was used to study the strapping technique and compare the application of ductile and brittle metal strips (i.e. S and T type strips). The two latter sets (B2 and B3) were especially made for comparing CFRP with the two types of strips for concrete confinement. The corners of prismatic specimens of the second and the third sets (i.e. B2, B3) were rounded with a radius of 2.5 cm, making it suitable for CFRP wrapping.

The material used for the concrete specimens included type I portland cement, local sand and gravel. The maximum size of the gravel was 12 mm. No additive was used in any of the mixes.

Applied strips had different widths, thicknesses and mechanical behaviors. Standard tensile tests were performed on three samples of each size of these materials and their average mechanical properties are shown in table 4. The moduli of elasticity of strips and FRP were 200 and 220 GPa, respectively. Ultimate strength, elastic modulus, ultimate strain and thickness of each layer of CFRP was 2800 MPa, 220 GPa, 1.55% and 0.176 mm, respectively. A summary of the mechanical properties of these materials are reported in the following table.

Table 3: Concrete Mix Designs (per Cubic meter)

Element	Batch1 (B1)	Batch2 (B2)	Batch3 (B3)
Cement	241	336	436
Water	205	205	205
Coarse aggregate	874	874	874
Fine aggregate	1025	930	830
W/C ratio	0/85	0/61	0/47
Design compressive strength (Mpa)	10	25	35
Corners radius	0	2.5	2.5
Number of specimens	14	8	8

Table 4: Mechanical Properties of Applied Strips

Material	Width (mm)	Thickness (mm)	Yield stress (kg/cm^2)	Ultimate stress (kg/cm^2)	Ultimate strain
S strip	16	0.5	1033	1033	0.01
T strip	32	0.8	8746	9975	0.07
CFRP	---	0.176	28000	28000	0.0155

(a)

(b)

Figure 1. Test setup and instrumentation a) strapped b) FRP wrapped

3. AXIAL STRESS-STRAIN BEHAVIOR

Axial and lateral strains of column specimens were obtained by measuring specimen deformations by LVDT. In Figure 2, axial and lateral stress-strain behaviors of two specimens of the first set of specimens (B1) are shown. These specimens were confined with brittle S strips at two distinctive spacing values.

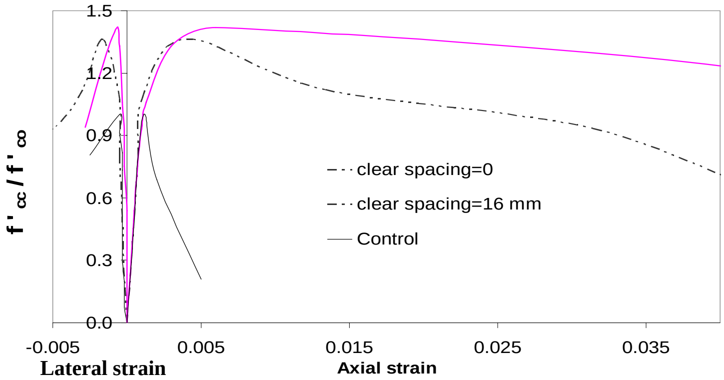
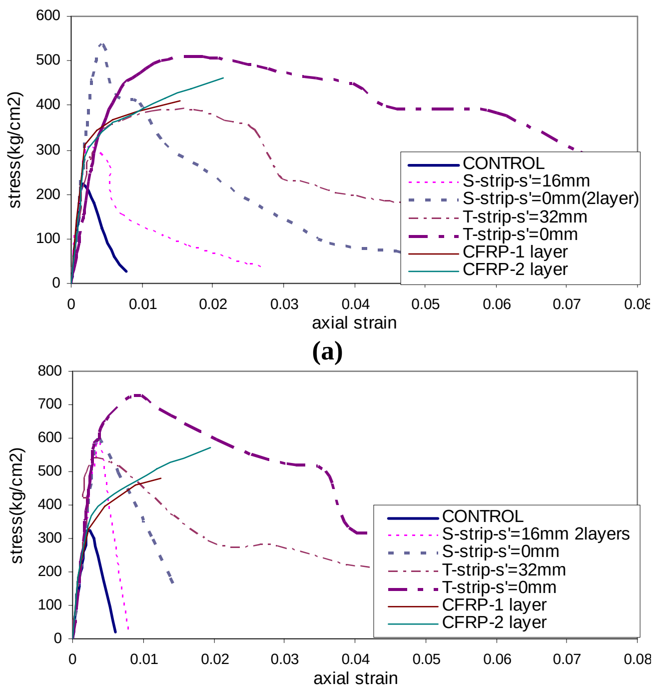


Figure 2. Normalized stress-strain of two confined specimens of B1 set strengthened with S strip

The vertical axis shows the provided increase in strength which is obtained by normalizing the measured stress to strength of plain concrete. It can be seen that the amount of volumetric ratio of confinement affects concrete strength and ductility. However because of the low strength of these specimens (in contrast to other results) the increase in strength is not as much as ductility enhancement. By considering the evolution of the lateral strains, it is obvious that the more confined specimen experiences less dilation.

Similarly, the stress-strain behavior of specimens of B2 and B3 sets that have been confined with one of the three applied confining materials are drawn in Figure 3. By comparing the behavior of specimens confined with brittle strips, ductile strip and CFRP it can be concluded that:

1. For a particular confining material, both strength and ductility of confined concrete increase with increasing the level of confinement.
2. For a similar confinement pattern, ductility of confined concrete is lower for specimens with higher strength concrete.
3. Although all of the three confining materials have similar elastic stiffness and both metal strips have similar strength values, but the form of stress-strain behavior of the triple sets of specimens differ apparently. As a matter of fact, ductility of confining material has dominated the stress-strain curve of confined concrete. As can be seen in the Figures, for a particular confining material, a similar form of stress-strain curve can be observed for various levels of confinement.
4. For a constant level of confinement with several confining materials, the higher the ductility of confining material, the higher the compressive ductility of confined concrete.



(a)

(b)

Figure 3. axial stress-strain of specimens confined with different materials for concrete specimens of a) B2 and b) B3 sets

It is also observed from these Figures that by using a ductile confining material, a very ductile compressive behavior for concrete can be achieved. This means great ultimate strain, better post-peak behavior and more thoughness and capability to absorb energy. It should be noted that theses curves correspond to prismatic specimens that traditionally can not be confined effectively and the obtained results for cylindrical specimens show much more ductility. For cylindrical specimens, it was observed that the ductile strip is capable to provide a very ductile behavior even for high strength concretes.[13]
From the above results and the results of other specimens presented by the authors [13], it can be concluded that for a similar confinement level, i.e. equal confinement pressure, ultimate strain and post-peak behavior of confined concrete is mainly dependent to the deformation capacity of the confining material.

4. ANALYSIS OF THE RESULTS

One of the measures for confinement level that has been widely used in the literature is the effective mechanical volumetric ratio of confining material, i.e. $K_e.\frac{\rho.f_y}{f_c^{'}}$. This has been also known as the effective confinement index. In this index, K_e is a ratio between 0 and 1 that takes the ineffectively confined regions between the longitudinal and transverse reinforcements into account. ρ is the volumetric ratio of the confining material , f_y and $f_c^{'}$ are yield strength of confinement and strength of plain concrete.
By considering the equilibrium of confined concrete, it can be shown that the effective confinement index equals with $K_e.\frac{2f_{ly}}{f_c^{'}}$, in which f_{ly} is the lateral confining pressure corresponding to the yield of confinement. This has also been shown by defining the concept of effective yield-based lateral confining pressure, i.e. $\frac{2f_{ley}}{f_c^{'}}$.
By analyzing the experimentally obtained results of this study and also experiments performed by Moghaddam and Samadi 2008, Frangou and Pilakoutas 1995 and also Mortazavi and Pilakoutas 2004, it was observed that the improvement of strength of confined concrete is strongly dependent to the effective confinement index. As can be observed in Figure 4, there is a fair relationship between the strength gain of confined concrete and the effective confinement index. Although, the available models for strength of confined concrete give relatively different formulas the upper and lower bounds of strength improvement ratio, can reasonably be determined with Richart1928 and Ahmad & shah 1982 models, respectively.

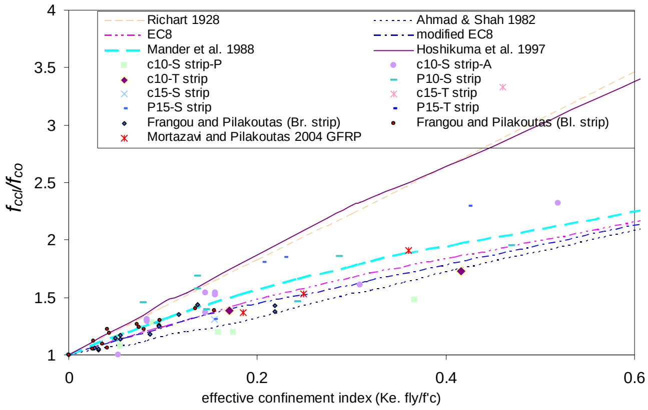


Figure 4. the relationship between effective confinement index and gain in strength

This strong relationship between effective confinement index and strength increase ratio can also be studied in particular for the three sets of specimens of this study which had different plain strengths. Figure 5 shows the strength gain ratio for specimens of this study that were retrofitted by any of the three confining materials of S strips, T strips and CFRP. It is observed that a close relationship exists between the variation of the strength increase ratio and the effective confinement index. This relationship is approximately the same for the three confining materials and three plain strength values.

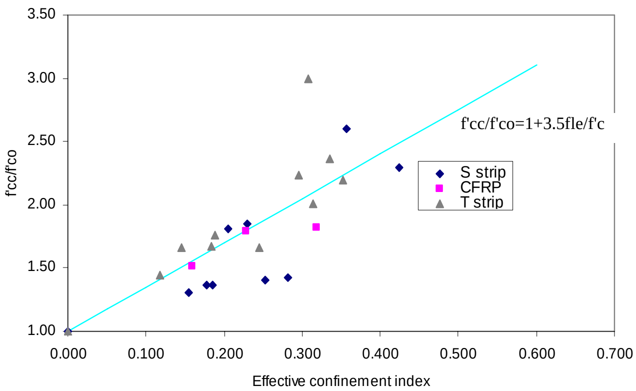


Figure 5. Strength Gain for Specimens of Three Batches Confined with one of the Triple Confining Materials

However, as observed in Figures 3, the gain in ductility of confined concrete is also dependent to the ductility of confining material and can not be described as only a function of confinement index. Therefore, a modification to the effective confinement index was done to take the deformation capacity of confining material into account. An equation with a form similar to that of Seible et al. 1995 as shown in table 2 was selected to predict the ductility gain of confined concrete and the modified confinement index was defined as the effective confinement index multiplied by the ultimate strain capacity of confining material. In order to study the ductility of confined concrete, ductility measure of CEB model code 90 was applied. A database of results of compressive tests on concrete confined with various materials was collected from the literature. The first data set of the database was the results of axial compressive tests on cylindrical 10*20 and 15*30 and prismatic 10*20 and 15*30 specimens that were confined with the two types of metal strips. These tests were previously conducted by the authors[13]. The second set of data includes test results of cylindrical 10*20 specimens confined with carbon or aramid FRP sheets by Watanabe et al. 1997. The third data set includes results of tests on cylindrical 15*30 specimens confined with CFRP sheets. The ratio between ultimate strains of confined and unconfined concrete specimens are drawn in Figure 8 versus the modified confinement index. As can be seen, the models of Seible et al. 1995 and EC8 did not suitably predict the ductility gain for neither of the steel-confined nor CFRP-confined concrete specimens. An analytical formula was obtained statistically and is as follows.

$$\varepsilon'_{cc}/\varepsilon'_{co}=1+2500\ (f_{le}/f'_{c}).\ \varepsilon_{ju}\ (f_{le}/f'_{c})<0.001 \qquad (1)$$

$$\varepsilon'cc/\varepsilon'co=3.5+550\ (f_{le}/f'_{c}).\ \varepsilon_{ju}\ \ (f_{le}/f'_{c})>0.001$$

The obtained formula of equation 1 is compared to the experimental data of the collected database. Figure 6 shows that, although the ductility gain data are more scattered than strength increase ratio values as presented in Figure 4, but equation 1 can give a better estimation of the increase in ductility due to confinement than the previous models. It is important to note that the experimental data of Figure 6 includes specimens with various shapes, sizes and confining materials and therefore the modified confinement index and equation 1 seem to have given good approximation of the ductility gain.

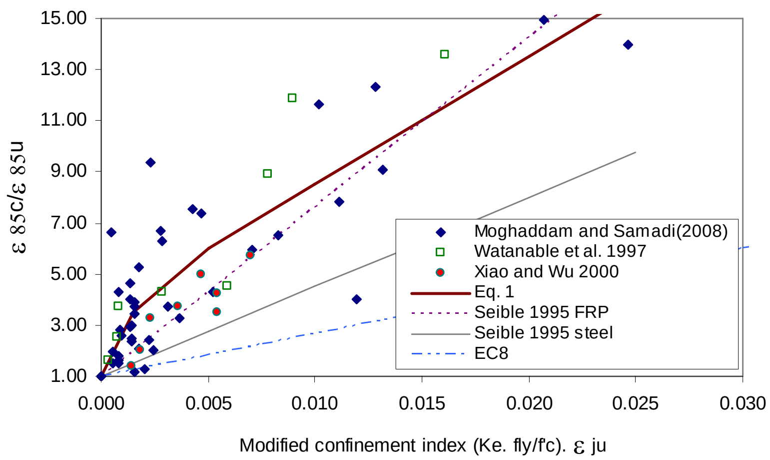


Figure 6. The Gain in Ultimate Strain for Concrete Confined with Various Materials

In order to verify the accuracy of the proposed equation, the experiments of this study were conducted. As mentioned earlier, prismatic 15*30 specimens with three levels of concrete strength were retrofitted with three confining materials, i.e. S type strips, T type strips and CFRP. The ratio of ultimate strain of confined concrete to that of unconfined one are drawn against the proposed ratio of modified confinement index in Figure 7. As can be seen in this Figure, the modified index for confinement and the proposed equation for ductility enhancement ratio due to confinement could give good approximation of the experimentally obtained values of this study. Adequate correlation can be observed between the experimental and analytical values especially when considering numerous differences than exist between the data points including strengths of plain concrete, confinement levels and confining materials.

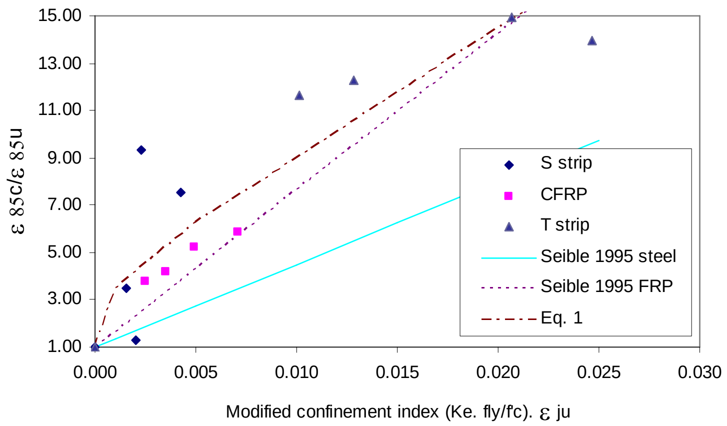


Figure 7. Gain in Ultimate Strain Versus Modified Confinement Index

5. CONCLUSION

Compressive tests were conducted on concrete specimens confined with various confining materials. In addition, some other test results were collected from the literature. Based on these results, some conclusions can be made. For all confining materials, by increasing the level of confinement, both strength and ductility of confined concrete increase. The confinement index (defined as the ratio of effective lateral pressure to strength of plain concrete) shows good correlation with the increase of strength of confined concrete for specimens with any size, shape and strength confined with both steel or FRP. Among various parameters, ductility of confining material plays the main role in determining the post-peak response of confined concrete. Then, for a particular confining material, by increasing the level of confinement the strength and ultimate strain of confined concrete are scaled without any significant change in the form of stress-strain curve of concrete.

The confinement index alone can not be used for approximating the ultimate strain of confined concrete. The modified confinement index, that was defined and applied in this paper, showed relatively good correlation with the gain in ductility.

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