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# Effectiveness Factor of Concrete Based on Lower - Bound Analysis of Deep Beams Strengthened with CFRP

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*Abstract-* **The effectiveness factor of concrete is existing to overcome the shortcomings of applying the plasticity theorem to analyse the behaviour of reinforced concrete and account for the limited ductility of concrete. The value of the effectiveness factor mainly depends on the material properties, the geometrical dimensions and the reinforcement details. There is disagreement among different codes of practice on the value of the effectiveness factor. The main aim of this research is to propose a new equation for the effectiveness factor of concrete that can be implemented in the lower-bound analysis of simply supported deep beams strengthen with CFRP. Moreover, the study assesses the use of different effectiveness factor expressions in the lower bond analysis of deep beams strengthened with CFRP. A model of a strut and tie is proposed to predict the final load for simply supported deep beams that fail to shear, taking into account the effect of the total depth of the deep beams and the angle of inclination of the strut according to the design codes. The accuracy of the proposed model is verified based on a database of 126 samples collected from previous studies. The analysis showed that the shear strength of deep beams strengthened with CFRP depends on more than one variable. Among the different effectiveness factor equations considered in this investigation, for the range of beams considered, the most accurate prediction was achieved using the proposed effectiveness factor equation with a mean of 1.00, a standard deviation of 17% and a coefficient of variation of 2.0%.**

*Index Terms:* **deep beams, strut-tie, strengthening CFRP, effectiveness factor, lower bound.**

## I. INTRODUCTION

Deep beams are relatively deep structural elements used to transfer concentrated loads such as beams bearing columns, pile caps, tank walls, foundation walls, offshore structures, and bridges. They receive a number of concentrated loads and distribute them to a number of reactions at the less fulcrum points.

The behavior of such structural components is described by the nonlinearity of the strain -stress distribution that develops as a result of a reduction in shear span-to-depth ratio (a/d). According to Eurocode 2 (EC2) [1], beams can be classified as deep beams when the ratio of span to depth is smaller than three. On the other hand, ACI 318-14[2] classifies beams as deep beams which satisfy (a) Clear span does not exceed four times the overall member depth h; or (b) Shear span does not exceed two times the overall member depth.

Deep beams have a different load transfer mechanism than shallow beams. In deep beams, the main load transfer element is a concrete strut formed between the loading point and the support. The shear resistance of deep beams dominates their load carrying capacity. Arch action, on the other hand, becomes the dominant load transfer mechanism in shallow beams, particularly after the formation of diagonal cracks. Furthermore, the capacity of shallow beams is more likely to be governed by strength in flexure, whereas the capacity of deep beams is governed by shear failure [3]. A deep beam is defined in current design codes as a discontinuity region with a nonlinear strain distribution. Deep beams should be analysed as a two-dimensional plane stress problem or as a three-dimensional element [2]. In this case, the classical theory of elasticity is only applicable to the behavior of deep beams prior to cracking. However, after cracking, there is a significant redistribution of stresses, return the elasticity theory invalid.

As a result, current design codes recommend that deep beams should be designed using either nonlinear analysis with the nonlinear strain distribution or the strut-and-tie model (STM) [4-6]. Since most of the applied load in deep beams is directly transferred to the support by strut and tie action, strut-and-tie model is the most reliable method for design purposes. The strut and tie model, invented by Ritter and Moersch in the late nineteenth century and developed by Schlaich, is a

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logical method for analyzing and designing deep reinforced concrete beams. This method is based on the theory of minimum plasticity theory in which structures are considered safe when all the elements have sufficient strength and sufficient deformation [7].

Therefore, the strut and tie model must be in equilibrium with external forces and/or forces from the adjacent B-regions, which follow Bernoulli's theorem, " plane sections remained plane after bending moment". as shown in Figure1.

In recent years, the reinforcement of concrete buildings has become of great interest to engineers, especially in large countries, as it requires spending huge budgets to maintain them every period of time. Therefore, methods of strengthening have been developed to raise the bearing capacity of buildings that has reached the end of their planned service life and to increase their bearing capacity when changing the operational function of the building. It also helps to protect structures against the impact of harsh environmental conditions and wars. Carbon Fiber Reinforced Polymer Sheets (CFRP), has a wide spread to reinforce concrete structures all over the world, CFRP is characterized by light weight, corrosion resistance, easy installation and high tensile strength.

Although CFRP has a widespread use in structural member strengthening, there is no mechanism in the design codes to use carbon fibers for strengthening. Thus, STM is currently incapable of predicting the shear strength of deep beams strengthened with CFRP. It is well known that, when applying the theory of plasticity in deep beams, the compressive strength of concrete is reduced by a factor called concrete effectiveness factor that occurs as a result of transverse stress and cracks [8].

Thus, several effectiveness factor equations have been proposed by researchers depending on the combination of factors that influence the reduction in compressive strength of the abutment without looking to the contribution of CFRP to shear strength. Previous studies suggested different values for the effectiveness factor. The ACI -440 code [9] suggested an effectiveness factor of 0.85 whereas Cory and Dolan [10] suggested a value between 0.75 and 0.85. On the other hand, an effectiveness factor of 0.7 was recommended by Khalifa [11]. However, these proposed values fail to accurately predict the shear strength of deep beams especially when main parameters vary and in some cases are unsafe. Therefore, this study aims to propose a new equation for the effectiveness factor of concrete is more validity and reliability in order to valeted evaluate the use of STM to predict the final shear strength with different parameters of simply supported deep beams strengthened with CFRP.

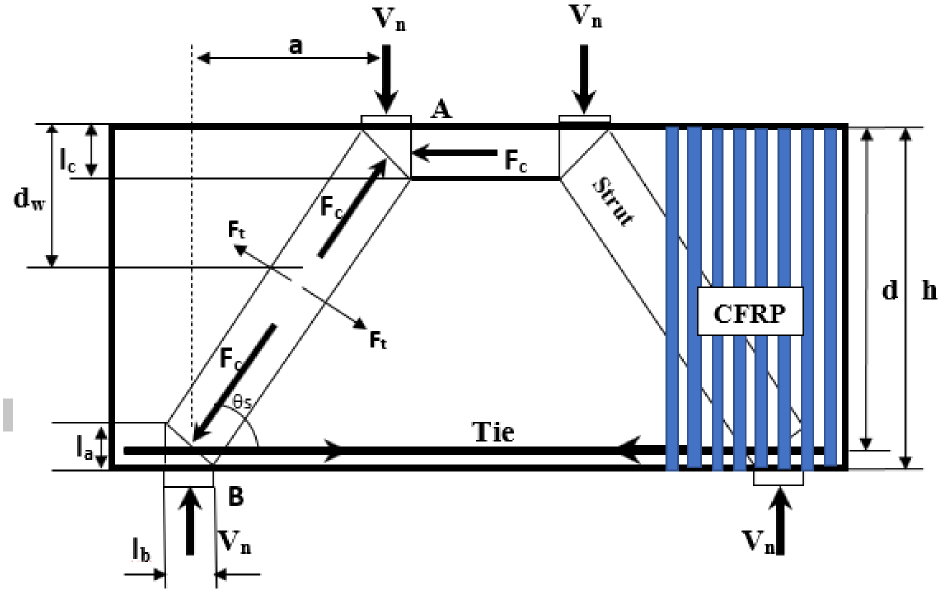

Figure1. Strut-and-tie model for simply supported deep beams.

## II. SIMPLY SUPPORTED DEEP BEAMS DATABASE

Experiments can provide key information on the behavior of RC deep beams. However, such tests can be expensive, time consuming and sometimes impractical due to the limiting capabilities of structural laboratories, especially when dealing with large elements. Therefore, in this study, statistical analysis will be used, drawing on a large database of previous experimental results on the use of STM for simple deep beams under the influence of two load points. A total of 126 deep beams were collected from eleven different previous investigations, as shown in Table1.

The database will be used to assess the various design guidelines for deep beams. To arrive at a more reliable effectiveness factor, some parameters that have an effect on the strength of concrete should be considered, including concrete compressive strength, the shear-to-depth ratio, the shear strength ratio, and the strength of carbon fiber-reinforced polymer. It should be mentioned that all the 126 sample in the data -base have web reinforcement and strengthened with CFRP.

Table 1: Database of RC simple deep beams

| **Reference** | **NO. of beam** | **Range of parameters** | | | | | | **Web reinforcement arrangement** |
|---|---|---|---|---|---|---|---|---|
| | | **L Mm** | **h Mm** | **b Mm** | **d Mm** | **a/d** | **$f_c'$ MPa** | |
| Hanoona et al.2017 | 6 | 1840 | 350 | 140 | 287 | 0.75<br>1<br>1.25<br>1.5<br>1.75<br>2 | 37.02 | Vertical<br>Horizontal<br>FRP |
| Godat et al.2013 | 14 | 6000 | 446 | 170 | 365 | 2 | 38 | Vertical<br>Horizontal<br>FRP |
| ZHAO YUJIE 2015 | 40 | 500<br>1200 | 500 | 100<br>225 | 465<br>350 | 1<br>0.5 | 26-42 | Vertical<br>Horizontal<br>FRP |
| Zhang et al. 2004 | 19 | 900 | 229 | 102 | 203 | 1.87<br>1.25 | 42-43 | Vertical<br>Horizontal<br>FRP |
| Cao etal.2005 | 12 | 2000 | 250 | 150 | 223 | 1.4<br>1.8<br>2.5<br>2.7<br>2.9 | 24 | Vertical<br>Horizontal<br>FRP |
| Li 2015 | 12 | 2000<br>2400 | 350 | 180 | 303 | 1<br>1.5<br>2<br>2.5<br>3<br>3.5 | 47-55 | Vertical<br>Horizontal<br>FRP |
| Mustafa 2021 | 2 | 2000 | 305 | 153 | 235 | 1.75<br>3.25 | 34.5 | Vertical<br>Horizontal<br>FRP |
| Panjehpoure et al.2014 | 6 | 1840 | 350 | 140 | 293 | 1<br>1.25<br>1.5<br>1.75<br>2 | 37.02 | Vertical<br>HFRP |
| Godat et al. 2010 | 4 | 900<br>1800<br>2700 | 200<br>400<br>600<br>600 | 100<br>200<br>300<br>300 | 166<br>330<br>498<br>498 | 2 | 51.2<br>51.2<br>51<br>51 | Vertical<br>Horizontal<br>FRP |
| Hanoon et al. | 3 | 1840 | 238 | 102 | 275 | 1<br>1.75 | 38<br>41.6<br>50 | Vertical<br>Horizontal<br>FRP |
| Diagna et al. 2003 | 8 | 2200 | 450 | 130 | 425 | 2.11 | 40 | Vertical<br>Horizontal<br>FRP |

Where L is the span length, d is the beam effective depth, b is the beam width, $h$ is the beam total depth, a/d is the shear span-to the depth ratio $f_c'$ is the concrete compressive strength.

In the database, as shown in Table 1, shear span-to-depth ratio (a/d), ranged from 0.5 to 3.5, the overall depth of the beams, $h$, varied between 200 to 600 mm and the span of the beams, $L$, ranged between 500 to 6000 mm. About half of the beams had a/d=2 while the highest number of beams had a/d ratio less than 2 as shown in Figure 2. Moreover, the tested beams having a compressive strength, $f_c'$ ranging between 20MPa and high compressive strength 50 MPa. Only 9 of the beams had a compressive strength higher than 50 MPa whereas a very small number of beams were made with concrete of a compressive strength less than 20 MPa as shown in Figure 3.

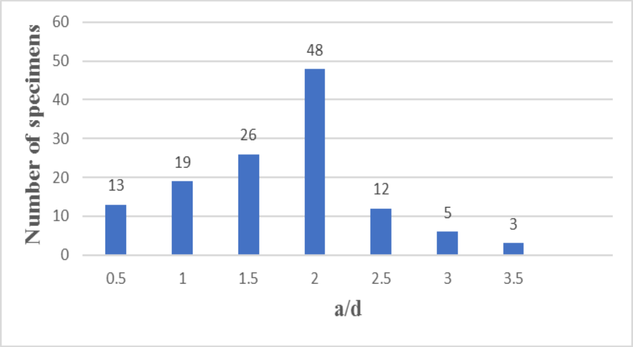

Figure 2. Distribution of a/d ratio of deep beams in the database

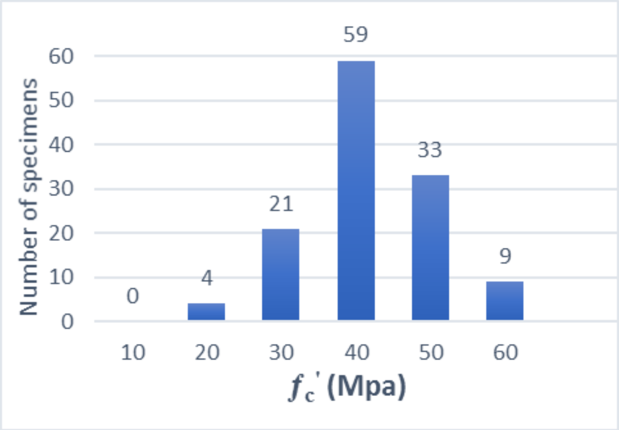

Figure 3. Distribution of compressive strength of deep beams in the database

## III. EFFECTIVENESS FACTOR OF CONCRETE

The effectiveness factor, $v$, is presented to overcome the limitations of using the plasticity theorem to analyse the behavior of reinforced concrete and to account for concrete's limited ductility [12]. The effectiveness factor's value is primarily determined by the material properties, geometrical dimensions, and reinforcement details. As shown in Table 2, different codes of practice disagree on the value of the effectiveness factor. According to the ACI318-14[2] code, the value of the concrete effectiveness factor is determined by the amount of vertical and horizontal reinforcement. Where the ratio of reinforcement in both directions is greater than 0.0025. However, the prismatic and bottle shapes in the distribution of internal stresses in the beam affect the value of effectiveness factor of concrete. This means that if the amount of web reinforcement meets the requirements in Table 2, the value of v is 0.64; otherwise, the value of v is 0.51. However, EC2 [1] suggested that effectiveness factor should depend on the value of concrete compressive strength. The Canadian Standard, on the other hand, suggests a value for the effectiveness factor based on the principal tensile strain of the steel reinforcement and the angle between the tie and the strut [4]. The principal tensile strain is approximated by ($\varepsilon 1 = \varepsilon s + \varepsilon s$ (0.002)/(tan)2), where $\varepsilon s$ is the tensile strain in the ties. For design purposes, $\varepsilon s$ can be thought of as the yield strain of the steel reinforcement obtained by performing a tensile test on the steel bars. In the current study, all of the beams tested had the same type of reinforcement, which means that the tensile strain is constant for all beams while the a/d ratio varies. As a result, the value of the effectiveness factor according to the Canadian Standard can be calculated based on the value of the $a/d$ ratio, as shown in Table 2.

Table 2: Equations of effectiveness factor v according to different design codes.

| **Reference** | **Equation Effectiveness factor** | **Notes** |
|---|---|---|
| **ACI 318-14** | $v$ = 0.85βs | $\beta_s = 0.75\ if: \sum \frac{A_{sl}}{b_{sl}} sin\alpha_1 \geq 0.003$<br>$\beta_s = 0.6\ otherwise$ |
| **EC2** | $v = 0.6\ (\frac{1 - f_c'}{250})$ | |
| **CSA23.3-04** | $v = \frac{1}{1.14} + 0.68(\frac{a}{d})^2$ | $\leqslant 0.85$ |

Note: $\beta_s$ is a factor to account for the effect of cracking and confining reinforcement on the effective compressive strength of concrete in a strut, $A_{si}$ is the area of surface reinforcement crossing the strut, $s_i$ is the spacing between the surface reinforcement bars crossing the strut, $b$ is the beam web width, $\propto i$ is the angle between the axis of strut and the surface reinforcing bars crossing the strut, $a$ is the shear span and $d$ is the effective depth of the beam.

On the other hand, a number of researchers suggested various equations for v. Three equations for v, as shown in Table 3, were chosen to be used in the analysis presented in this paper. These formulas were chosen based on various parameters. Hanoon studied the effect of carbon reinforcement on the final shear strength of deep beams, proposing a stress distribution factor that reduces the value of the effectiveness factor of concrete to be between (0.25-0,85), and thus reduces the shear strength of deep beams [13]. The study concluded that deep beams may fail by concrete splitting that can be resisted by the longitudinal and transverse reinforcement, CFRP sheets, and concrete tensile strength. However, Godut [14] discovered that increasing the amount of vertical reinforcement and increasing the number of carbon sheet layers along the shear span raises the maximum shear capacity. However, another study suggested that one of the most important factors affecting the effectiveness factor of concrete is the compressive strength, and the shear span to the arm extending between the upper and lower longitudinal reinforcement centers (a/z) ratio [15]. Nielsen equation [16] for the effectiveness concrete factor ranged from 0.55 to 0.73 as it depends only on the compressive strength of concrete.

Table 3. Equation's effectiveness factor v according to different research.

| Reference | Equation Effectiveness factor | Notes |
|---|---|---|
| Hanoon (2017) | $v = \left(1 - \frac{kT_s \, sin^2\theta_s}{A_c f_t}\right)$ | $f_t = \frac{kA_s f_{y \sin \theta_s}}{A_c / \sin \theta_w} + \frac{2A_w f_{yw\, si\, n(\theta_s + \theta_w)}}{A_c / \sin \theta_w} \frac{d_w}{d} + \frac{2n_f A_{FRP} f_{y.FRP} \sin(\theta_x + \theta_w)}{A_c / \sin \theta_w} \frac{d_w}{d} + f_{ct}$ |
| Foster (1996) | $v = \frac{1}{1.14 + \left(0.64 + \frac{f_c'}{470}\right)\left(\frac{a}{z}\right)^2}$ | $z$ is the vertical distance between two nodes. |
| Nielsen (1984) | $v = 0.8 - \frac{f_c'}{200}$ | $f_c' \leq 55\, MPa$ |

where $fc'$ is the concrete compressive strength, k is the stress distribution factor, $d$ is the beam effective depth, As, $A_w$, and $A_{FRP}$ are the total areas of longitudinal reinforcement, web reinforcement, and CFRP sheet, respectively; $f_y$, $f_{yw}$, and $f_{yFRP}$ are the yield strengths of longitudinal reinforcement, web reinforcement, and ultimate strength of CFRP sheets, respectively; $n_f$ is the number of CFRP sheet layers; and $f_{ct}$ is the tensile strength of concrete, $d_w/d$ is introduced to account for different levels of web reinforcement, $\theta_s$ is the inclined angle of the strut, $\theta_w$ is the inclined angle of the web reinforcement to the horizontal axis

## IV. STRUT-AND-TIE MODELING

Existing design codes consider deep beams design using strut and tie model STM to be a more reliable method and lead to a safer design. In this section, comparisons are made between the experimental results from literature and STM results suggested by different design codes, namely ACI Building Code (318-14) [2], Euro Code 2 (EC2) [1] and Canadian Standards for the Design of Concrete Structures (CSA23.3- 04) [4].

The main aim of the current study is to propose a new equation for the effectiveness factor of concrete for the analysis of simple deep beams strengthened with carbon fiber. The proposed equation will be used in STM to predict the final shear strength of all samples in the database collected from previous studies. Effectiveness factor equations from different design codes as well as those from previous studies will be assessed in order to arrive at reasonable predictions.

The total ultimate applied load for STM is estimated using a set of equations shown below:

$$P_u = 2 \times V_n \qquad 1$$

$$V_n = v \times A_{str} \times f_c' \times \sin \theta_s \qquad 2$$

$$A_{str} = b_w (l_a \cos \theta_s + l_b \sin \theta_s) \qquad 3$$

Where $V_n$ the nominal shear strength, $v$ is the effectiveness factor of concrete, $f_c'$ is the cylinder compressive strength of concrete, $b_w$ is the beam width, $\theta_s$ is the angle between the concrete strut and the longitudinal axis of the beam, $l_a$ is the depth of the top nodal zone, $l_b$ is the width of the load bearing plate, h is the total height of the beam.

In the above equations, the concrete effectiveness factor is the only difference between the three design codes considered in the current comparison. Each design code indicates a different formula for the effectiveness factor as it was presented in Table 2. Furthermore, a number of researchers suggested different formulas for the effectiveness factor as it was shown in Table 3. Three equations were chosen to be used in the presented analysis. The selected formulas depended on different physical and engineering properties and varied from one research to another. Nielsen [16] proposed a formula for $v$ based on the value of . The value of $v$ obtained from this formula ranges from 0.3 to 0.8 for concrete strength up to 100 MPa. However, this formula was modified by Foster [15] to reflect the effect of volume as effective depth and shear extension ratio. Hanoon [13] indicated that the effectiveness factor of concrete shall be a function of concrete strength and major tensile and compressive strains in reinforcement of concrete.

As shown in Table 4, the most accurate prediction of design codes was obtained by the ACI 318M-14 with a mean, a standard deviation and a coefficient of variation of 1.03, 17% and 2.9%, respectively. For other equations it can be concluded that, although the mean value for the predictions was reasonable, the variations of the results around the mean were very scattered as indicated by the large values of standard deviation and coefficient of variation. It is worth noting that, as shown in Figures 4 and 5, using these equations to predict the shear strength of deep beams strengthened with CFRP give highly scattered and mostly over-conservative results and, at the same time, yield very unsafe results Therefore, such equations cannot be used to predict the shear behavior of RC deep beams with an appropriate margin of safety.

Table 4: The mean, SD and COV for STM predictions of load capacity of RC simple deep beams using different values for the effectiveness factor

| **Reference** | **Mean** | **Standard deviation (%)** | **Coefficient of variation (%)** |
|---|---|---|---|
| ACI 318-14 | 1.03 | 17 | 2.9 |
| EC2 | 1.7 | 30 | 9 |
| CSA23.3-04 | 2.6 | 95 | 45 |
| Hanoon (2017) | 1.08 | 57 | 32 |
| Foster (1996) | 2.7 | 43 | 28 |
| Nielsen (1984) | 2.37 | 51 | 26 |

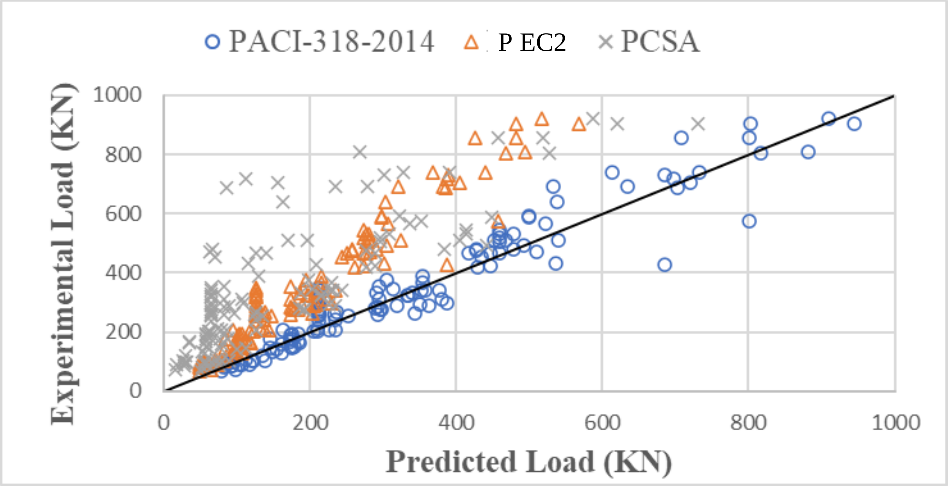

Figure 4. Comparisons between experimental results of RC simple deep beams and predictions of STM using effectiveness factors suggested by different design codes

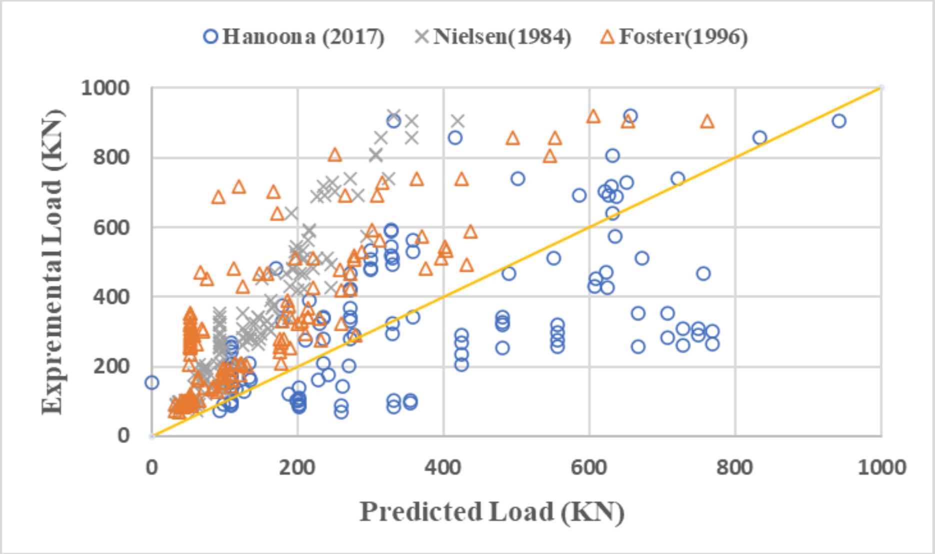

Figure 5. Comparisons between experimental results of RC simple deep beams and predictions of STM using effectiveness factors suggested by different researc

## V. EFFECT OF COMPRESSIVE STRENGTH

Concrete compressive strength is one of the most important factors influencing the bearing capacity of deep beams, particularly those with low a/d ratio. The load in deep beams is transmitted through compression supports, and the resistance of these supports is primarily determined by the compressive strength of concrete. Moreover, failure is sometimes caused by compression support failure. Because shear strength is a function of compressive strength, El-Sayed [17], demonstrated that the shear strength of deep beams increased by 45 percent when increasing the compressive strength of concrete by 10%. This increase is not proportional because aggregate cracking at final load generates less friction in high strength concrete (>60 MPa) than in normal strength concrete, indicating that as the strength of the concrete increases, it becomes more brittle, and the efficiency of the support decreases. Similarly, Vecchio and Collins [18], investigated the effect of concrete strength greater than 60 MPa on the concrete effectiveness factor and discovered a significant decrease in the shear capacity of deep beams. However, Smith and Fantiotis [19] indicated that has a significant influence on the shear capacity of deep beams. Their findings also showed that the shear capacity increases with high web reinforcement and low compressive strength up to 23 MPa. Londhe [20], on the other hand, demonstrated that the compressive strength of concrete ($f_c'$ = 24 to 37 MPa) has only a negligible effect on the shear strength of deep beams.

Through the samples that were obtained analysis for the deep reinforced concrete beams in this research, we note the effect of compressive strength of concrete on the value of the effectiveness factor by using statistical analysis as follows:

Based on a study of the effect of concrete compressive strength on the effectiveness factor in design practices, we note that the value of the effectiveness factor in the American $f_c'$code ranged between (0.7-1.2) in the range of low and high concrete resistance, showing good and close results in the range of 40 MPa, taking into account the type of strut and the stress distribution mechanism. The European Code, on the other hand, assigned more conservative values for the presence of a safety factor related to the properties of brittle materials that exhibit plastic behavior. Whereas the Canadian Code considered that the only factor that has a relationship in reducing beam resistance is the shear span to depth ratio, so was the outcomes are extremely conservative as showed Figure 6.

By different researches, also it can be concluded that, the variatons of the results around the mean were very scattered as showed Figure 6 The accuracy of the predictions was much higher than those of beams of design codes Hanoon's predictions are closer to accuracy than the rest of the studies, but they are not conservative in the case of increased principal tensile strength where lead to less safe prediction.

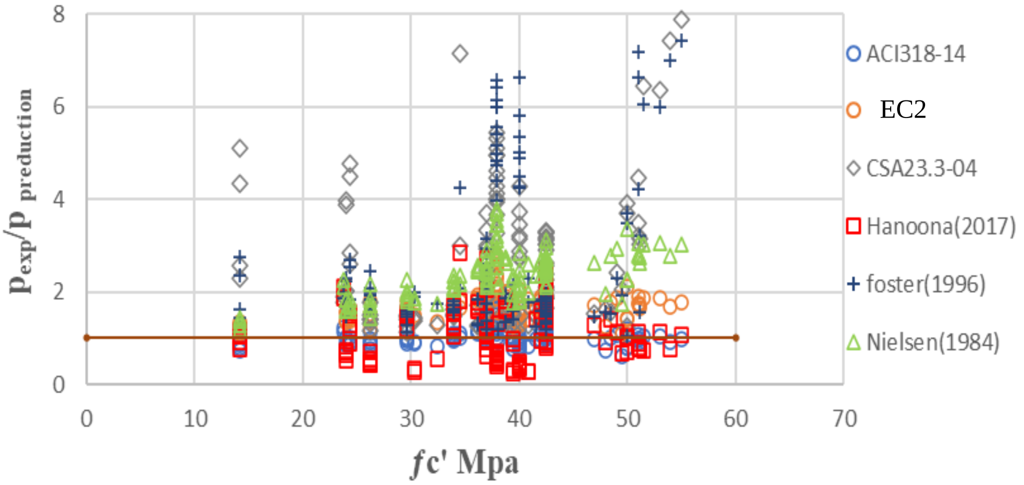

Figure 6. Effect of concrete compressive strength on the ultimate load prediction of STM using effectiveness factors suggested by different design codes and different researchers

## VI. EFFECT OF SHEAR SPAN-TO-DEPTH RATIO

Although STM is a new analysis tool, ACI 318, Eurocode, CSA Specifications have developed design criteria for discontinuous areas based on the Strut-and-Tie method [2]. When a diagonal crack occurs, the bending behavior of the beam cracking takes precedence over the actual arc action of the beam cracking [5]. Experiments have shown that the shear strength of a deep beam increases with depth. The effect of the shear span ratio with a value ranging from (0.5-3.5) is shown safely on the proposed equation of the code ACI 318-14, while there is a high conservation of the code EC2 and a large deviation for values of the code CSA23.3-04. as shown in Figure 7.

We also can note that the predictive shear strength increases if the shear span ratio is less than 3 in the proposed equation for Hanoon [13], whereas with values between (0.5-3.5), the predictive shear strength of

Nielsen[16] and Foster[15] less to give more conservative values, indicating the need for further research.

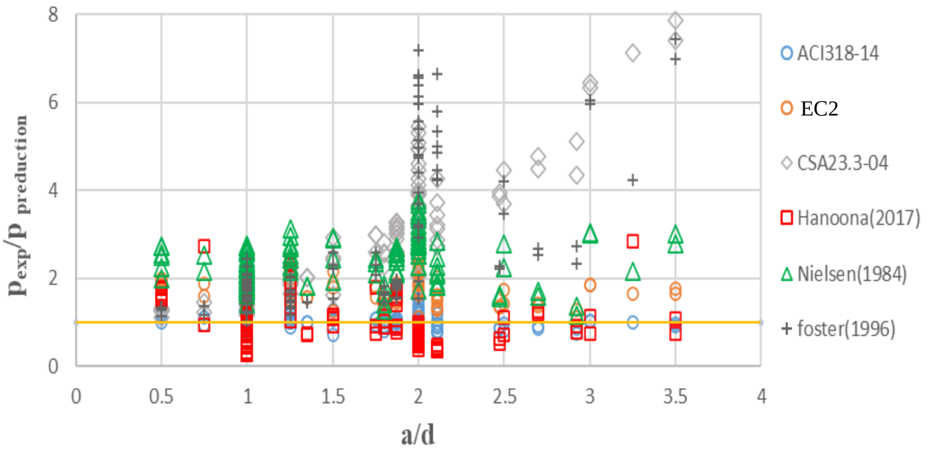

Figure 7. Effect of *a*/*d* ratio on the ultimate load prediction of STM using effectiveness factors suggested by design codes and different researchers

## VII. PROPOSED EFFECTIVENESS FACTOR FOR DEEP BEAM STRENGTHENED CFRP

A new formula for the RC effectiveness factor was proposed using regression analysis of the samples of all the deep beam samples that were collected for the current study in Table 1. The proposed equation was based on the results of the European code equation investigations [1], and the properties of the materials on which the previous research equations were based such as the compressive strength of concrete, the shear span to the depth ratio, and tensile strength of shear rebar and carbon fiber reinforced polymer. Previous research proved that the ratio of reinforced steel stirrups along the shear span led to an increase in shear strength with an increase in the number of reinforcing layers [21-24], in addition, other studies confirmed that the strengthening of deep beams using carbon strips to the near surface (NSM), Recover 93% - 94% of the original capacity using the brace and peg model. On the other hand, the final shear strength is the sum of three components: strut strength, vertical reinforcement, and carbon fiber reinforced plastic panels [25].

The proposed equation is 4 and 5 shown below:

$$v = 1.1 - 0.5\,(0.6\,(1 - \frac{f_c'}{250})) + 0.04(\frac{a}{d})^{-1} + 0.005\,(\frac{\mathbf{1}}{\boldsymbol{f_t}}) \qquad 4$$

$$f_t = \frac{kA_s f_{y\,\sin\,\theta_s}}{A_c/\sin\theta_w} + \frac{2A_w f_{yw\,si\,n(\theta_s+\theta_w)}}{A_c/\sin\theta_w}\,\frac{d_w}{d} + \frac{2n_f A_{FRP} f_{y.FRP}\,\sin(\theta_x + \theta_w)}{A_c/\sin\theta_w}\,\frac{d_w}{d} + f_{ct} \qquad 5$$

where $f_c'$ is the concrete compressive strength, $A_c$ is area of deep beam cross-sectional, $A_w$ is area, web reinforcement and AFRP is area CFRP sheet, $f_{yw}$, is the yield strengths of web reinforcement, $f_{y.FRP}$ is the yield ultimate strength of CFRP; $n_f$ is the number of CFRP sheet layers, $\theta_s$ is the inclined angle of the strut; $d_w/d$ is introduced to account for different levels of web reinforcement.

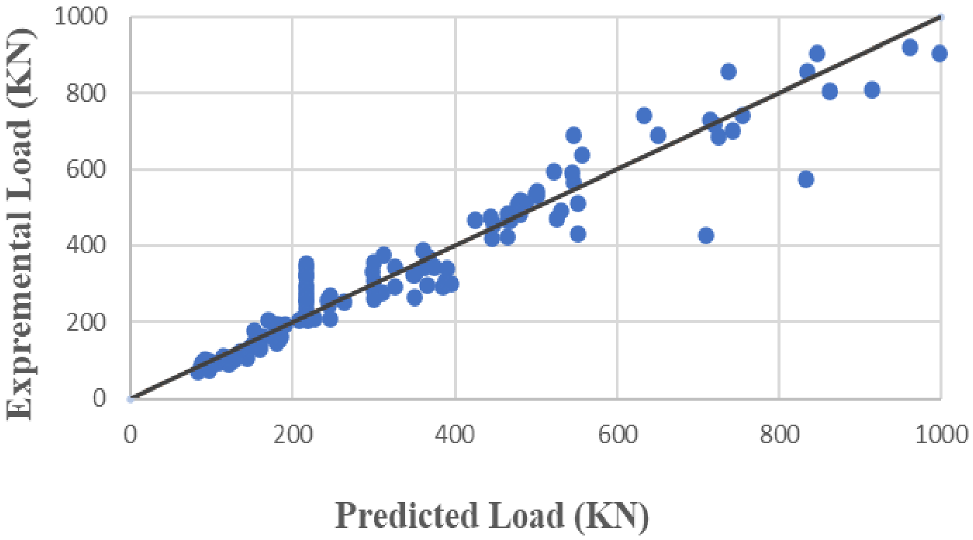

Figure. 8. predictions using effectiveness factor suggested in the current study.

The comparisons between the experimental load capacity of simply-supported RC deep beams and the predictions of the analysis using the proposed concrete effectiveness factor equation are presented in Figure 8. It can be observed that the proposed concrete effectiveness formula achieved more accurate predictions for the load capacity of the database than the previous studied equations.

The STM predictions were slightly more accurate than those of the design codes, achieving a mean of 1, standard deviation of 17%, and a coefficient of variance of 2%. However, the loading capacities obtained from the STM decrease as the shear span to depth ratio decreases. Moreover, concrete effectiveness were slightly more accurate than predictions generated by other efficiency factor equations proposed in the literature. In general, the proposed efficacy factor made very factor predictions using the proposed equation accurate predictions of the range of packages considered. However, further validation of the proposed formula is needed because the current experimental data available on simple carbon fiber-reinforced polymer deep beams RC are still limited.

## VIII. CONCLUSIONS

This paper presented a detailed examination of various effectiveness factor equations proposed by various design codes of practice and previous research investigations for predicting the load capacity of RC simply supported deep beams strengthened with carbon fiber reinforced polymer.

The investigation was based on the use of the effectiveness factor equations, available in the design codes and previous research studies, in the strut and tie model. Since studies are still based on the use of polymer-reinforced carbon fibers, as reinforcing materials to increase the capacity of deep beams in shear, there are not the constant contribution of these fibers among the influencing factors on the efficiency of the effectiveness of concrete. Therefore, this study suggested a new effectiveness factor equation to be used the lower bound analysis of deep beams strengthened with GFRP.

Based on the analysis presented in this paper, the following conclusions are drawn:

- There is a clear difference between various design codes and previous studies when it comes to selecting the appropriate effectiveness factor for concrete. The majority of the available effectiveness factor equations are based on a single parameter. However, it appears that a combination of multiple variables such as compressive strength, shear span-to-depth ratio, shear reinforcement ratio, and carbon sheet reinforcement, have a significant influence on the concrete effectiveness factor.
- The strut-and-tie model recommended by different design codes showed contradictory results for all beams considered. The ACI Building Code (318M-11) predictions were more accurate than those of the EC2 and Canadian Code (CSA23.3-04).

The effectiveness factor formulas proposed in the current study for the lower-bound analysis of simply supported deep beams resulted in accurate predictions in comparison with the experimental results collected from previous studies.

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