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Development and Calibration of an Efficiency Factor Model for Recycled Aggregate Concrete Struts

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ABSTRACT

In the strut-and-tie (STM) method of design, the internal mechanism of flow of forces is represented by hypothetical truss in which the behavior of the beam is controlled by the strut connecting load and support points. The strength of such strut is correlated to the shear capacity of the deep beam through a factor called the strut efficiency factor. Different efficiency factor models have been recommended by various internationally accepted codes. However, none of the codes takes into account the effect of recycled aggregates in concrete. Although some codes yield conservative results, these predictions are not sensitive enough to the recycled aggregate content. Therefore, an efficiency factor model sensitive to recycled aggregate concrete and easy to operate is much desired. In this work, published results of laboratory tests on deep beam specimens made of concrete consisting of recycled aggregates were considered for the analysis, employing a suitable strut-and-tie model. All these deep beams were originally designed by sectional or empirical method. Based on regression analysis of the outcomes of the STM analysis, an efficiency factor model has been proposed which takes into account the effect of recycled aggregates in concrete. Subsequently, scaled deep beam specimens containing recycled aggregate concrete were cast and tested in the laboratory in order to calibrate the proposed strut efficiency factor model. The yield of proposed efficiency factor model was compared with the predictions of the selected internationally accepted code provisions. It is found that the predictions of proposed efficiency factor model give consistent and comparable results.

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1. INTRODUCTION

A strut-and-tie model (STM) is a method used in structural engineering to analyze and design reinforced concrete structures, especially for structural members containing D-regions such as corbels, beam-column joints, deep beams, pile caps, etc. [1-4]. Theoretically, STM is a lower bound method in which the mechanism of load transfer is represented by a set of struts and ties attached with node under the condition of plane stress. The capacity of the elements, such as struts and ties, of STM is then calculated, taking into account equilibrium and constitutive relations. The strut connecting load point and support point, hereafter called the bottle-shaped strut, plays a key role in the failure mechanism of deep beams. While transferring the load, due to direct compression between load and support point indirect tension is generated which reduces the strength of such strut. To represent this reduction in strength, the coefficient, or factor, 'β_s' is applied to the strut. Various codes name this factor as follows: ACI 318-14 [5] defines it as strut coefficient, Eurocode 2 [6] describes it as strength reduction factor, JSCE [7] guidelines simply name it reduction factor, and AS-3600 [8] expresses it as strut efficiency factor. Although different codes assign different nomenclature to this factor, in this work it is termed the strut efficiency factor and used in the forthcoming description. In general, the crushing strength of a concrete strut is referred to as its effective strength and is given by the following formula (Equation (1)):

$$f_{cu} = \beta_s f_c' \tag{1}$$

where, β_s is an efficiency factor having a value between 0 to 1, f_{cu} is the effective concrete compressive strength

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in the strut (as per ACI 318-14 [5]), and f'_c is the cylinder compressive strength of concrete. Various sources in the literature recommend differing values of strut efficiency factors, with perhaps the simplest recommendations being those of ACI 318-14, wherein the nominal compressive strength of concrete in the strut is pre-multiplied by an efficiency factor varying between 0.6 and 1. Limiting concrete compressive stresses in struts specified by selected design codes is presented in Table 1.

For suitability and adaptability with respect to the changing environment, industrial wastes including construction and demolition (C&D) waste have been recognized as a possible source to substitute various ingredients of conventional cement concrete. For example, GGBFS, fly ash (FA) and other ashes [9] and silica fume to partly replace an OPC, GGBFS to replace FA and extracts of C&D to replace aggregates in new concrete [10, 11]. Utilizing recycled concrete aggregate (RCA) extracted from waste concrete for producing new concrete has some economic and environmental benefits, as the aggregates occupy 60 to 75% volume of the concrete mixture. Even with these advantages, it hasn't been extensively adopted by the construction industry, especially for structural applications. The literature review reveals that the majority of the investigations concentrated on the processing, characterization, rheology of RAC [12, 13] along with NAC [14] or on the physical and mechanical properties of concrete made with such aggregates [15]. The focus on structural application of this concrete has been more recent [16, 17]. Even the structural performance of RCA concrete under various actions has not been comprehensively investigated. Most of the reported studies focused on flexural behaviour with a few on the behaviour of shear-critical elements like corbels, beam-column joints, deep beams, pile caps, etc. Structural action in such members is governed by shear, and the internal forces can be conveniently represented by strut-and-tie models. As discussed in the preceding paragraph, struts are the compression members in STM, and the literature review indicates that bottle-shaped struts are particularly susceptible to splitting failure [18, 19]. The use of such relatively soft and porous recycled concrete aggregates in concrete is likely to raise concerns about safety and serviceability. Code provisions to design such critical struts are either empirical or not robust enough. The efficiency factor is a critical parameter for the design of bottle-shaped struts, and most of the available efficiency factor models in the literature are limited in scope and account for the effects of a very narrow range of parameters. None of the recommendations in the literature for strut-and-tie modelling is calibrated for application to recycled aggregate concrete.

TABLE 1. Comparison of code provisions on recommended strut efficiency factors

Code Name	$\beta_{s,code}$	Required Transverse or Web Reinforcement
ACI 318-14 [5]	Unreinforced bottle-shaped strut: 0.60	--
	Reinforced bottle-shaped strut: 0.75	• $\rho_T = 0.003$ (For $f'_c \leq 6000$ psi) • $\sum\left(\frac{A_{si}}{b_s s_i}\sin\alpha_i\right) \geq 0.003$ (For $f'_c > 6000$)
AASHTO [20]	$\frac{1}{(0.8+170\,\varepsilon_1)} \leq 0.85$	Orthogonal grid of reinforcement bars near each face, i.e., $\rho_H \geq 0.003$ or $\rho_V \geq 0.003$
Eurocode 2 [6]	$0.6\left(1-\frac{f_{ck}}{250}\right)$	• Partial discontinuity $T=\frac{1}{4}\left(\frac{b-a}{b}\right)F$ • Full discontinuity $T=\frac{1}{4}\left(1-0.7\frac{a}{h}\right)F$ • $T = F_{sc}\,A_{st}$
AS-3600 [8]	$\frac{1}{1.0+0.66\cot^2\alpha_s}$	Transverse reinforcement required to resist design bursting force in accordance with Clause 7.2.4 of AS-3600
Present Study	$\left(\frac{f_t}{12+0.002R}\right)$	--

It is thus obvious that, the use of the efficiency factor in the design equations of STM is a simplified approach and doesn't take into account all the factors affecting the strut capacity. More specifically, it does not consider the effect of modified properties of the concrete when alternate materials such as recycled aggregates, are used in place of conventional ingredient since the provisions for β_s are originally made for NA-concrete. Therefore, concerns have been raised about the applicability of current code provisions (such as ACI 318-14 [5], AASHTO [20], Eurocode 2 [6], and AS-3600 [8]) for RCA-concrete [21]. In the present investigation, a mathematical model for β_s is developed by performing regression analysis on a database of 123 RCA-concrete deep beam specimens extracted from the literature. This proposed model is a function of compressive stress, 'f'_c', replacement percentage of NA with RCA, 'R', and is capable of estimating the shear capacity of RCA-concrete specimens in general and the capacity of critical struts like the bottle-shaped strut in specific. Further, the modified form of the model in terms of tensile strength 'f_{ct}' is also discussed. Besides the validation of the test results of the beam specimens reported in the literature, the proposed efficiency factor model is calibrated by testing deep beams containing recycled aggregate concrete.

2. STM ANALYSIS OF SELECTED BEAM SPECIMENS

The specimens satisfying the deep beam criteria of ACI 318-14 [5] were considered for this investigation. All the selected deep beam specimens which were originally designed using empirical equations or by the sectional method are reanalyzed by applying STM. A suitable strut-and-tie model was superimposed on the geometry of selected beam specimens in order to carry out STM analysis. Further, the capacity of the critical strut was calculated, which was subsequently used to estimate the shear capacity of the beams. A total of 123 beam specimens were filtered out from the database. The selection of 123 beams was made on the basis of the qualifying condition that the beam specimens should be composed of concrete containing aggregates partly or fully replaced by recycled aggregates. The beam specimens tested and reported by Choi et al. [22], Han and Chung [23], Singh et al. [24], Fathifazl et al. [25], Kim et al. [26], Etman et al. [27], Aly et al. [28], Al-Zahraa et al. [29], Lian et al. [30], Arabiyat et al. [31] and Li et al. [32] have considered for this study. All the specimens have the limits of shear span to depth ratio of 0.54 to 2.50, a compressive stress from 16.7 to 58.60, and a replacement level ranging from 0% to 100%.

A typical beam (RAC30-H1.5) tested by Choi et al. [22] under a four-point bending test is considered to illustrate the STM analysis procedure. The beam specimen was 1840 mm long, 400 mm deep, and 200 mm wide, with an effective span of 1440 mm, as shown in Figure 1. To carry out analysis, the suitable STM is superimposed on the geometry of selected beam specimens.

Once the strut-and-tie model to describe the flow of forces in a beam was assigned, the required dimensions were easily determined. The node dimensions were assigned to find out strut width at the strut and the node interfaces at both ends, and the minimum value of the two was considered as the width of the bottle-shaped strut, w_s. Next, the effective transverse reinforcement ratio was determined from the provided web reinforcement in the

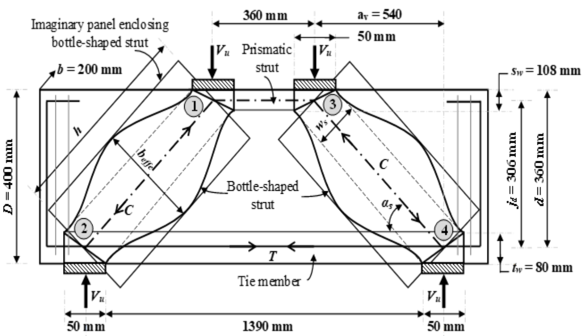


Figure 1. STM superimposed over the specimen tested by Choi et al. [22]

Beam Dimension: D, b, d, a_v
Material Properties: $f'_c, f_y, f'_y, f_{yv}, f_{yh}$
Reinforcement Details: $A_{st}, A_{sc}, A_{sh}, A_{sv}$
Bearing Plate Dimensions: l_b

Fix the depth of tie (t_w) and depth of top node or depth of prismatic strut (s_w)
$t_w = 2\,(D-d)$ and $s_w = \left(\frac{A_{st}\,f_y - A_{sc}\,f'_y}{f'_c\,b_s}\right)$

Determine the lever arm (j_d) and inclination of strut (α_s)
$j_d = D - \left(\frac{t_w + s_w}{2}\right)$ and $\alpha_s = \tan^{-1}\left(\frac{j_d}{a_v}\right)$

Calculate the width of strut (w_s)
$w_s = l_b \sin\alpha_s + t_w \cos\alpha_s$
$w_s = k\, l_b \sin\alpha_s + s_w \cos\alpha_s$

Calculate the theoretical capacity of strut (C_{Th})
$C_{Th} = \beta_{s,code} . b. w_{s,min} . f'_c$

Calculate measured capacity of strut (C_{expt})
$C_{expt} = F. \sin\alpha_s$

Measured efficiency factor by equating theoretical capacity and the measured capacity ($\beta_{s,measured}$)
$\beta_{s,measured} = C_{expt}/b. w_{s,min} . f'_c$

Compare the code strut efficiency factor ($\beta_{s,code}$) with measured strut efficiency factor ($\beta_{s,measured}$)

Figure 2. Flowchart to demonstrate STM analysis procedure

form of either stirrups or an orthogonal grid. With the use of equilibrium equations, support reactions are found as usual. The theoretical capacity of the strut is estimated as $C_{Th} = \beta_s.b.w_{s,min}.f'_c$. Thereafter, the truss model was solved by applying conditions of equilibrium to determine compressive force (C_{expt}) in the critical strut using the relation $C_{expt} = F / \sin\alpha_s$. Where, F is the magnitude of the nearest associated support reaction. It should be noted that in the case of a four-point or symmetric three-point bending test, the support reaction is equal to half of the total applied load, whereas in the case of an eccentric three-point bending test, the reaction is equal to the fraction of the applied load. Finally, the efficiency factor was measured by equating the theoretical capacity and the measured capacity of the critical bottle-shaped strut as follows [Equation (2)]:

$$\beta_{s,measured} = C_{expt}/b. w_{s,min} . f'_c \tag{2}$$

3. DEVELOPMENT OF PROPOSED EFFICIENCY FACTOR MODEL

In deep beams, load is primarily transferred through strut action, in which direct compression generates indirect transverse tension. It leads to a reduction in the capacity of bottle-shaped struts. Considering this fact, the following mathematical relationship for β_s is derived by regression analysis of the outcomes of STM analysis of selected specimens.

$$\beta_s = \left(\frac{0.56\sqrt{f_c'}}{12+0.002R}\right) \tag{3}$$

The numerator of Equation (3) represents the root of concrete compressive stress, and the denominator contains the relation that is the function of replacement level in percentage, *R*. Unlike flexural member design procedures, concrete tensile strength cannot be neglected in the design philosophy of shear critical members such as deep beams, especially those containing recycled aggregate concrete. Because, in the case of deep beams, usually the failure occurs due to splitting instead of crushing of concrete. Therefore, the proposed form of the equation can be more effective if the effect of split tensile strength is accommodated in the model. The value of the numerator in Equation (3) matches with the equation for the tensile strength of concrete recommended by ACI 318-14, $f_t = 0.56\sqrt{f_c'}$. Thus, the direct value of split tensile strength (f_t) can be used in place of $0.56\sqrt{f_c'}$. It should be noted that, this relationship of concrete tensile and compressive strength is for NAC; however, it can be used for RAC as the effect of RCA replacement can be mitigated by the reduced compressive strength of RAC. The revised Equation (3) will take the following form [Equation (4)]:

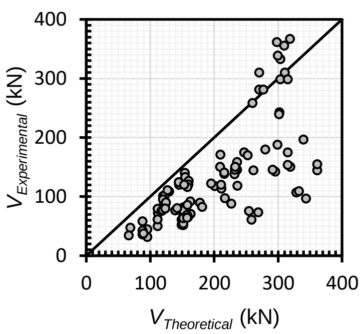
$$\beta_s = \left(\frac{f_t}{12+0.002R}\right) \tag{4}$$

The comparison of $\beta_{s,code}$ recommended by various codes along with the proposed model is compiled in Table 1.

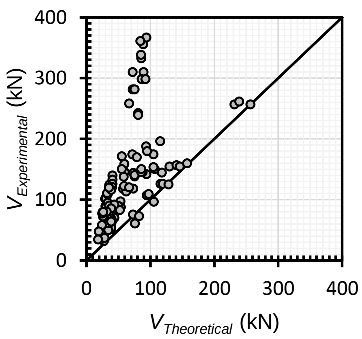
As deliberated in the introduction, the strength of a strut is dependent on the effective compressive stress of the concrete mass that occupies the strut. It may be noted that the effective compressive stress in a bottle-shaped strut is affected by transverse stresses within the strut. Therefore, once f'_c is established, f_{cu} can be obtained by multiplying the value of β_s with the minimal of the cross-sectional areas at the two ends of the strut. Figures 3(a) and 3(b) reveal the comparison of the measured shear capacities of the selected beam specimens with and without the application of the β_s. The plot shows measured shear capacity on the ordinate and thermotical shear capacity on the abscissa. A line of 45^0 inclination is drawn to indicate the conservatism. The values of measured shear capacity lying above this line imply conservative results, whereas the values below this line indicate unsafe results. It has been observed that without the application of any efficiency factor, only 8% of the results were conservative (Figure 3(a)), on the contrary after the application of the proposed efficiency factor, around 95% of the results became conservative (Figure 3(b)). Thus, the exercise highlights the importance of the application of the strut efficiency factor in STM design procedures. The efficiency factor in any form takes care of known and unknown limitations of the STM procedures.

4. EXPERIMENTAL PROGRAM

The purpose of the beam tests was to calibrate the effectiveness of the proposed strut efficiency factor model against recycled aggregate content in concrete. The deep beam specimen was so configured that the applied load was transferred to the nearest support through a strut action. The dimensions of the beam specimens were kept constant for each replacement level of natural aggregates, as typically depicted in Figure 4 and in Table 2. The beam is proposed to be tested in 3-point bending by applying a concentrated load on the top



(a) Measured versus predicted shear capacity (Without use of efficiency factor)



(b) Measured versus predicted shear capacity (With use of efficiency factor)

Figure 3. Role of strut efficiency factor in STM Design Procedure

face of the beam at distances of 625 mm from both the supports (Figure 4). The distances were selected in such a way that the load transmitted through the bottle-shaped strut became exactly equal to the load carrying capacity of the deep beam. Therefore, the strut inclination with the adjacent tie becomes 30°. The internal force system in the deep beam could be represented using the truss models shown in Figure 4.

It can be seen that the inclined strut between nodes 3 and 4 transfers a major fraction of the applied load, *P*, to the support. Since sufficient space is available in the web of the beam for the dispersion of the compressive stress trajectories in this strut, it can be designated as a bottle-shaped strut. It is this strut which has been targeted for validation of the proposed efficiency factor model in particular and for a study of the behavior of RCA concrete bottle-shaped struts in general. It may be noted in Figure 4 that the strut inclination of 30° is close to the lower-bound strut inclination angle specified by the ACI 318-14 [5]. The design details of the deep beam specimens with concrete mix proportion are summarized in Table 2.

The control concrete mixture containing natural coarse aggregates was designed by the absolute volume method as per the provisions of IS 10262 [33] and the RCA concrete was prepared by the direct replacement of natural aggregates by weights as per a predefined percentage. Control concretes are identified in this investigation by the generic name of NCA-concrete whereas the concretes containing various fractions of recycled aggregates are identified by the generic name RCA-concrete. The nomenclature for the test specimens is defined in Table 3. Except for the substitution of the NCA fractions with the RCA, the other ingredients in these two concrete types were nominally the same. It should be noted that all the concrete ingredients conformed to the relevant Indian standards.

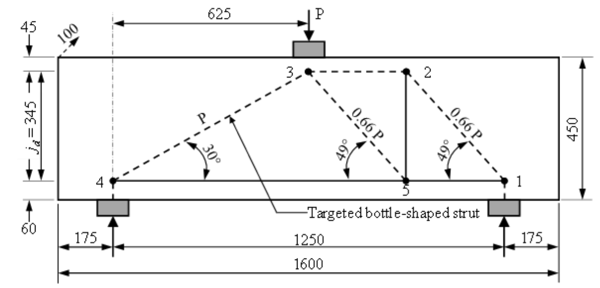


Figure 4. Truss models for the deep beam specimens (Concentrated load applied at 625 mm from nearest support)

TABLE 2. Details of deep beam specimens and concrete mixture

Specimen ID	*R*	w_s (mm)	j_d (mm)	A_{st} (mm^2)	Steel Provided
DB-R-0	0%	103	345	628	2-12Ø +2-16Ø
DB-R-50	50%	103	345	628	2-12Ø +2-16Ø
DB-R-100	100%	103	345	628	2-12Ø +2-16Ø

Concrete mix proportion (quantities in kg/m^3):

W/C Ratio	Cement	Fine Aggregate	Coarse Aggregate
0.45	370	720	1140

*All beams are 1600 mm long, 450 mm deep, and 100 mm thick

Thermo-Mechanically Treated (TMT) deformed steel bars of nominal diameters of 8 mm, 12 mm, and 16 mm were used to create the reinforcement cage as depicted in Figure 5. For obtaining the mechanical properties, all the steel bars were tested in a 1000 kN capacity tensile testing machine as per the procedure recommended in IS:1608. The longitudinal tension reinforcement in the deep beams was determined on the basis of the calculated tie forces near the beam soffits. Since the focus of this investigation was to study the effect of concrete strength and the replacement level of NA, the bottle-shaped strut region was kept free from transverse reinforcement. For the remaining region, nominal transverse reinforcement in the form of an orthogonal grid was provided. Depending upon the detailing of the reinforcement, steel cages were assembled in the laboratory, and a selection of these cages is shown in Figure 5. The reinforcement cages were placed inside steel formwork at the appropriate cover depth using concrete cover blocks, and casting was done in the laboratory.

TABLE 3. Summary of test results

Specimen ID	f'_c (MPa)	P_{cr} (*kN*)	P_u (*kN*)	w_{cr} (mm)	$\beta_{s,Measured}$	$\beta_{s,Predicted}$
DB-R-0	40.00	141	308	0.12	0.77	0.29
DB-R-50	37.50	128	294	0.12	0.76	0.28
DB-R-100	37.00	120	263	0.16	0.68	0.27

Key to specimen ID: The first two places in the nomenclature are the short form of deep beam, the third place-holder implies replacement of NA, and the last two digits indicate percentage replacement. For example, the specimen ID DB-R-50 stands for a deep beam with 50% replacement.

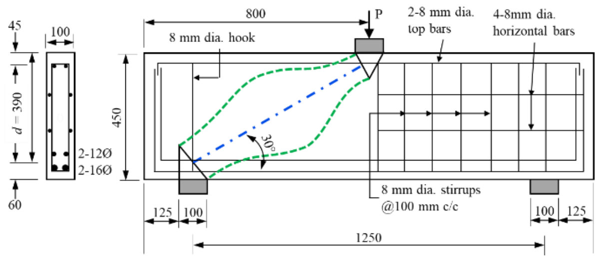


Figure 5. Detailing of reinforcement in the beams with the transversely unreinforced bottle-shaped struts

After 28 days, the beams were ready for testing. All beam specimens were subjected to 3-point bending over a simply supported span of 1250 mm. The load was applied by a 1000 kN capacity hydraulic jack, and the applied load was recorded with the help of a 1000 kN load cell. At the load point, a mild steel bearing plate of size 100 mm × 100 mm × 40 mm was used to transfer the applied load to the beam, whereas two plates of the same dimensions were used to simulate supports. A typical test setup for a deep beam test is presented in Figure 6. The loading rate was so configured that failure would occur in about 20 to 25 loading steps. The failure invariably occurred due to longitudinal splitting in the targeted bottle-shaped strut.

5. RESULTS AND DISCUSSION

In order to examine the behavior of RCA-concrete bottle-shaped strut, a series of deep beam tests were conducted. All the deep beam specimens were tested under the symmetric three-point bending test. The response of the tested specimens in terms of load at first crack (P_{cr}) and ultimate load (P_u) was recorded. Load-deformation characteristics and crack patterns were also assessed. The crack width (w_{cr}) at service load was measured. All the relevant test results are summarized in Table 3.

5. 1. Load-deformation Characteristics Figure 7 illustrates the load-deflection relationships of the selected transversely unreinforced deep beam specimens for varying degrees of RCA replacement. Three replacement levels of NA 0%, 50%, and 100%, respectively, have been considered. The overall stiffness measured in terms of the slope of the load-deflection relationship decreased with an increase in the RCA replacement level.

To evaluate the serviceability behaviour of the bottle-shaped struts, the cracking behaviour, particularly the maximum crack widths, was monitored at every load increment. None of the service load crack width values was greater than the limiting values of 0.3 mm and 0.41 mm recommended in IS-456 [34] and ACI 318-14 [5], respectively.

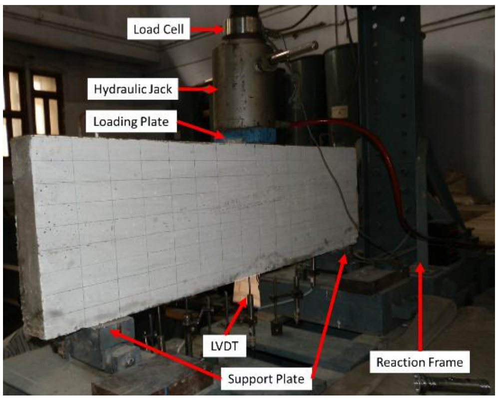


Figure 6. Typical test setup for a deep beam test

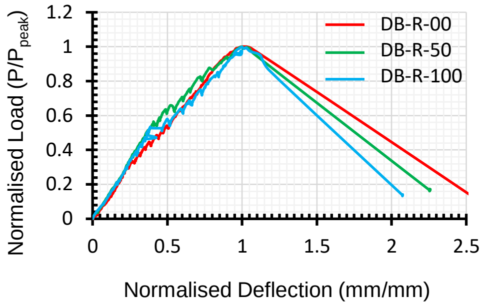


Figure 7. Load deformation relationship

Attention is drawn to the service load crack widths in the specimens, in all of which the targeted bottle-shaped strut is transversely unreinforced but the measured crack widths are all less than the limiting value of 0.3 mm. Of these three specimens, the beam DB-R-00 is made of natural aggregate concrete, whereas the specimens DB-R-50 and DB-R-100 are made of recycled aggregate concrete. One of the objectives of providing transverse reinforcement is to control cracking in the bottle-shaped struts.

The above results suggest that even in the absence of transverse reinforcement, the aim of crack control is still met. This observation may be read in the context that ACI 318-14 allows the use of transversely unreinforced bottle-shaped struts. It is emphasized here that besides controlling cracking behaviour, transverse reinforcement sustains structural capacity after splitting and imparts ductility. Hence, in line with the recommendations of Brown and Bayrak [35] transversely unreinforced RCA concrete bottle-shaped struts should not be used in practice. In Figure 8, cracking patterns of recycled concrete beams and a control beam are shown. The

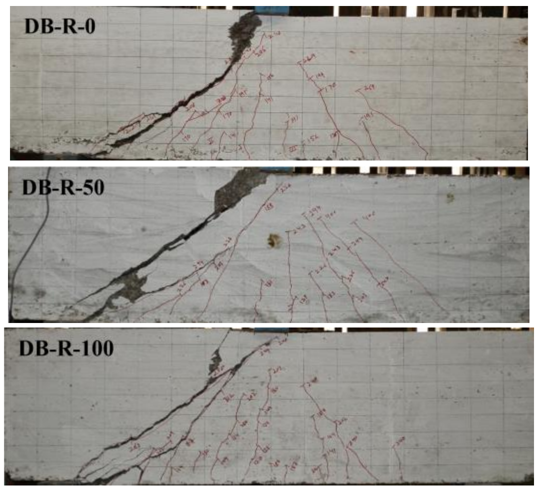


Figure 8. Comparison of crack patterns

natural concrete beam has only one prominent crack leading to failure, while the recycled concrete beam has at least two prominent cracks, indicating that recycled aggregate concrete has a relatively higher crack density.

5. 2. Appraisal of the Proposed Model The objective of the present work is to develop a simple, robust, and sensitive strut efficiency model for the concretes containing substitute materials like recycled aggregates. Another objective is to check the fit of the existing models recommended by various codes for recycled aggregate concrete. In order to meet these objectives, measured strut efficiency factors of the selected deep beam specimens are compared with the predictions of various selected models, along with the predictions of the proposed model. It is convenient to incorporate the results of deep beam tests carried out in our laboratory with the results of beam tests reported in the literature to avoid separate and repeated description. Factually, there are two sets of measured β values: a) The β values measured by processing the results of beam tests collected from the literature, and b) The experimentally investigated β values. The plots of the measured and predicted strut efficiency factors are presented in Figures 9 through 13. To differentiate outsourced and experimentally investigated values of strut efficiency factors, the experimentally measured values are indicated by squares, whereas the processed values β (of the outsourced specimens from the literature) are represented by circles.

Figure 9 depicts the comparison of measured-to-predicted efficiency factors by ACI 318-14 [5]. As can be seen in Figure 9, the ACI 318-14 gives either 0.6 or 0.75 based on the concentration of effective transverse reinforcement. Therefore, two straight vertical clusters of predicted values appear in the plot, which is practically not desired. Because, ideally, if the predictions of any model are reasonably accurate, then the scatter of the values is expected to lie above but along a 45° inclined line. Moreover, it is observed that ACI 318-14 recommendations generate a good number of unconservative results. This is mainly due to the fact that ACI 318-14 recommended efficiency factors are arbitrary values which depend on strut type. The mean and coefficient of variance (CoV) for the measured to predicted capacity were 0.95 and 0.42, respectively. The degree of conservatism, the ratio of measured to predicted strut efficiency factor, is observed to be significantly lower, i.e., 35.77 %. It should be noted that to maintain uniformity in the comparison, the reduction factors assigned for the quality of workmanship are not assigned. Application of this '$\emptyset$' factor improves the degree of conservatism; however, sometimes it leads to overly conservative estimations.

Figure 10 depicts the measured-to-predicted shear strength by AASHTO [20]. It has been observed that, the

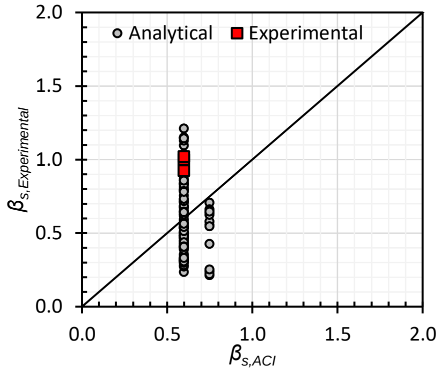


Figure 9. Comparison of measured strut efficiency factors with predictions of ACI 318-14

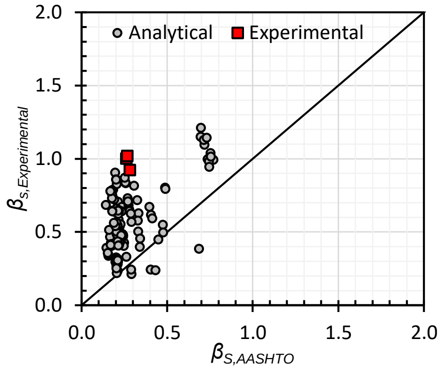


Figure 10. Comparison of measured strut efficiency factors with predictions of AASHTO

AASHTO recommendations not only have a good degree of conservatism but also a scatter that is comparatively more realistic. The only disadvantage is that AASHTO predicts overly conservative values and, also like other code provisions, is not sensitive to RCA content in the concrete. This might be a result of the overestimated value of 'ε_1'. As the AASHTO suggested model is based on the MCFT. The mean and CoV are 2.25 and 0.42, respectively.

The Eurocode 2 [6] predictions are also comparatively less conservative, and the predicted values are found concentrated in one vertical cluster (Figure 11). This might be due to the fact that, the Eurocode 2 model is a single parameter model and is the function of concrete compressive strength alone. The average value of the conservatism is greater than unity, and the calculated degree of conservatism is 52.85% and CoV is 0.40.

A comparison of measured-to-predicted strut efficiency factors by AS-3600 [8] is presented in Figure 12. Like AASHTO [20], AS-3600 [8] predictions have a reasonably acceptable degree of conservatism, is calculated at 93.50%. The predictions are overly conservative and insensitive to the type of concrete. The Efficiency Factor Model adopted by AS-3600 is a

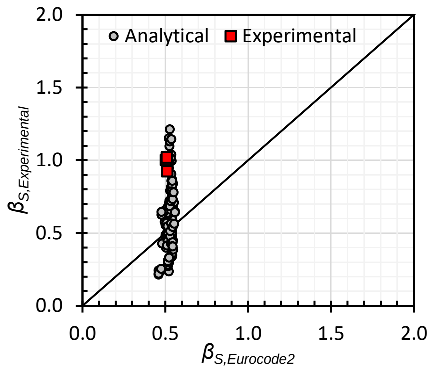


Figure 11. Comparison of measured strut efficiency factors with predictions from Eurocode 2

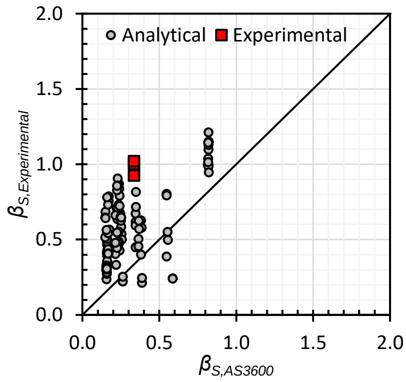


Figure 12. Comparison of measured strut efficiency factors with predictions of AS-3600

modified version of Collins and Mitchell [36] relationship. The mean value measured-to-predicted ratio was 2.33 and CoV was 0.42, respectively.

The proposed strut efficiency factor model takes into account the effect of the replacement level of RCAs, *R* and *f'c*. Therefore, it becomes sensitive to the recycled aggregate contents besides the strength of the concrete. This results in comparable predictions as those of the international code provisions. With an average value of 2.35 and a CoV of 0.44, proposed model predictions are more consistent in comparison with the predictions of selected models (Figure 13). The degree of conservatism of the proposed model is about 95%, which is relatively higher than that of ACI 318-14 [5] (35.77%) and Eurocode 2 [6] (52.85%), slightly lower than that of AASHTO [20] (95.93%), and slightly greater than AS-3600 [8] (93.50%). Besides comparable predictions, the trend of the prediction is in agreement with the trend of measured efficiency factors.

An important point is to be noted that, in this analysis, neither any additional safety factors for the load or materials were applied nor factors like *Ø* factor for the quality of workmanship. This is done in order to achieve uniformity in the analysis of predictions. However, the

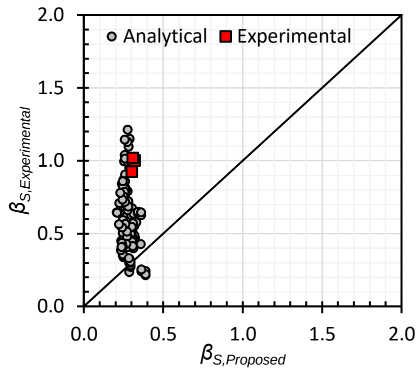


Figure 13. Comparison of measured strut efficiency factors with predictions of the proposed model

application of suitable safety factors and reduction factors would result in a higher level of conservatism and more economical designs. Hence, the above predictions of various codes which seem unconservative may result in conservative predictions on application of partial safety factors and load factors.

6. CONCLUSIONS

- The strut efficiency factor models recommended by various codes produce either unconservative results or overly conservative results. These models are not sensitive to the concrete containing substitute materials like recycled aggregates.
- The STM analysis reveals that the efficiency factor decreased with increased content of recycled aggregates in the concrete. Similar findings have been reported by previous studies.
- A strut efficiency factor model has been developed through regression analysis of reported test data. The proposed model accommodates the effect of concrete compressive strength and the replacement level of natural aggregates. However, accommodating the tensile strength of concrete in the proposed model makes it more rational. In the absence of measured concrete tensile strength, the relationship between compressive strength and tensile strength recommended by ACI 318-14 may be utilized.
- The proposed strut efficiency factor model has been evaluated by comparing its predictions with the measured values in the deep beam tests. Unlike the overly conservative predictions of other models, the proposed model yields moderately conservative predictions.
- The proposed model is sensitive to RCA content in the concrete. Therefore, the trends of forecasts from the proposed model are noticeably similar to the trends of measured values. On the contrary, other

models do not consider the influence of recycled aggregates on β_s. Hence, they do not exhibit similar trends, although the predictions may be conservative.

- To calibrate the efficacy of the proposed model, a series of deep beam tests were carried out. All the beam specimens were designed by STM and made up of concrete containing partly or fully replaced natural aggregates with recycled coarse aggregates. Predictions of the $\beta_{s,proposed}$ for bottle-shaped struts in deep beams made either of two concrete types were also conservative and relatively more accurate.
- The degree of conservatism of the proposed model is about 95%, which is comparable to the predictions of internationally accepted codes.

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Persian Abstract

چکیده

در روش طراحی پایه و گره (STM)، مکانیسم داخلی جریان نیروها با خرپا فرضی نشان داده می‌شود که در آن رفتار تیر توسط بار و نقاط تکیه‌گاه کنترل می‌شود. استحکام چنین پایه با ظرفیت برشی تیر عمیق از طریق عاملی به نام ضریب راندمان پایه در ارتباط است. مدل های مختلف ضریب کارایی توسط کدهای بین المللی پذیرفته شده مختلف توصیه شده است. با این حال، هیچ یک از کدها تأثیر سنگدانه های بازیافتی در بتن را در نظر نمی گیرند. اگرچه برخی از کدها نتایج محافظه کارانه ای به همراه دارند، اما این پیش بینی ها به اندازه کافی به محتوای بازیافت شده حساس نیستند. بنابراین، یک مدل ضریب کارایی حساس به بتن سنگدانه بازیافتی و کارکرد آسان بسیار مطلوب است. در این کار، نتایج منتشر شده از آزمایش‌های آزمایشگاهی بر روی نمونه‌های تیر عمیق ساخته شده از بتن متشکل از سنگدانه‌های بازیافتی، با استفاده از یک مدل پایه و اتصال مناسب برای آنالیز در نظر گرفته شد. تمامی این تیرهای عمیق در ابتدا با روش مقطعی یا تجربی طراحی شده اند. بر اساس نتایج تجزیه و تحلیل رگرسیون از STM، یک مدل عامل کارایی پیشنهاد شده است که اثر سنگدانه های بازیافتی در بتن را در نظر می گیرد. متعاقباً، نمونه‌های تیر عمیق مقیاس‌شده حاوی بتن سنگدانه‌های بازیافتی ریخته‌گری شدند و در آزمایشگاه به منظور کالیبره کردن مدل فاکتور بهره‌وری استرات پیشنهادی ریخته‌گری شدند. بازده مدل ضریب کارایی پیشنهادی با پیش‌بینی مفاد کد منتخب پذیرفته شده بین‌المللی مقایسه شد. مشخص شده است که پیش‌بینی‌های مدل عامل کارایی پیشنهادی نتایج منسجم و قابل مقایسه ای به دست آمده است.