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CONCRETE SHEAR RESISTANCE ENHANCEMENT FACTOR DEVELOPMENT

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ABSTRACT
Concrete shear resistance capacity is a serious problem despite the several improvements attempts through different models. Certainly, improvement in concrete shear assessment will prolong the structural service life. Thus, the need for more research works in order to improve on the drawback in the current European code formulation. Therefore, this paper presents a suggestion for mitigation of shear failure through the improvement of shear performance enhancement that employs a more rational scheme to the development of concrete shear resistance factors. The result from the numerical examples given herein shows a considerable improvement in the concrete shear resistance estimation of about 11%. This shows that the developed shear resistance factors will significantly improve the EC2 shear formulation when applied.
Keywords: *Reinforced concrete, Concrete shear, Eurocode.*

INTRODUCTION
Several slab design cases have shown that shear stress concentration at the column-slab interface can be more critical than the flexural failure, and under such case shear governs the design (Park and Gamble, 2000). In a slab member exposed to concentrated load, punching shear problem is unavoidable; and this may result into punching failure (Balomenos *et al.*, 2014; Qian and Li, 2013). Hence, the necessity of checking slab for shear performance, and the need for improvement in method that formulates slab shear capacity is vital (Lantsoght, van der Veen, de Boer, *et al.*, 2015). Concrete shear resistance is a cause of concern in slab designs and as such several attempts have been made to suggest models through different empirical studies (Antonio *et al.*, 2013; Ju *et al.*, 2015; Shehata and Regan, 1989). These attempts were based on previous development by many authors (Hewitt and Batchelor, 1975; Kinnunen and Nylander, 1960) that sprung up from the late 1960. Their work led to proposals and subsequent formulations in various codes and standards that provides for empirical calculation of shear parameters with equations. It is important to note that, many of these empirical equations are found to predict shear performances conservatively (Collins *et al.*, 2008), and this may be connected to the presence of uncertainties in both the input and output design variables.

Significantly, the geometric input properties greatly influence the shear performance of Reinforced Concrete (RC) slab (Mostafaei *et al.*, 2011), while enhancing the ultimate capacity of RC structures shear capacity primarily depends on the slabs depth and flexural reinforcement provisions. The relevant European code (EC2, 2008) places much emphasis on the flexural reinforcement ratio, and this may be the reason why EC2 (2008) methodology is more precise in comparison with other code formats like the American code (ACI 318-2005) that does not evaluate the steel reinforcement ratio. However, it is noteworthy that there is no known shear values estimation flaws from the use of other design codes other than the EC2 (2008) formulations (Vainiūnas *et al.*, 2015).

Improvements in proper concrete shear assessment will prolong structural service life. Over the years, the different assessment methods and proposals presented, aimed to provide working tools in that respect. However, a recent study shows the underestimation of shear capacity by the European code formulations (that is concrete shear resistance is insufficient and low), despite the additional increase in shear capacity due to gain in concrete strength because of hydration. This is true because the development of the empirical formulae for shear strength capacities is found to be conservative (Ju *et al.*, 2015). Hence, the underestimation expressed concern in the European code approach for RC slabs concrete shear resistance capacity is a huge setback that requires attention. Therefore, this study addresses the challenge by suggesting an approach to developing schemes for the concrete shear performance enhancement.

In flat slabs, the estimation of shear failure defines its ultimate strength capacity, while the slab depth and column geometry have great influence on their shear strength capacity (Theodorakopoulos and Swamy, 2002). The conservative nature of the current European code shear failure prediction places more emphasis on the flexural failure (Lantsoght *et al.*, 2011; Pilakoutas and Li, 2003): however the concrete shear resistance value is largely underestimated. This is because the prediction fails to capture the presence of an additional increase in shear capacity overtime due to concrete strength gain which is necessitated by the hydration process. This scenario is generally understood because of the aggregate locking capacity (Lantsoght *et al.*, 2011). Pilakoutas and Li (2003) study demonstrated the inadequacy of shear reinforcement in curtailing shear failure, because the reinforcement bars may not have reached its yielding point before failure (Wang *et al.*, 2008). All these show the deficiency of the present empirical concrete shear estimation method.

Lantsoght, van der Veen, and de Boer (2015) presented a reliability-based expression for RC slab shear capacity according to EC2 (2008) provision and the findings show the underestimation of the resisting shear capacity. This corroborates the statement that shows that the development of the empirical formulation for concrete shear strength is flawed (Ju *et al.*, 2015). The shear resistance check found in EC2 (2008) is clear. For example, the concrete shear resistance shall be at least equal to $0.035k^{1.5} f_{ck}$.

However, the reported result fails to take into consideration this particular requirement. In this study, the use of the code extension that takes into account the minimum concrete shear requirement is followed.

Generally, concrete compressive strength, longitudinal reinforcement ratio, and slab effective depth influences the shear capacity of RC slab. Shehata and Regan (1989) investigation in the early 1960 reveals that a previous work by the authors Kinnunen and Nylander shows that slab rotation, χ, is factor that influences the shear capacity of RC structures. Thus, when increasing the χ value, the punching shear capacity considerably decreases even without subjecting the structure to additional load increment.

METHODS

Loadings presence on slabs necessitates the needs for stresses check near the support (Bond *et al.*, 2006). Generally, it is required to ensure that the concrete shear stress capacity, $v_{Rd,c}$ is sufficient enough to counter the applied shear stress, v_{Ed}, and this forms the basis for the shear capacity violations for this study. Hence, concrete shear capacity is a critical issue when dealing with flat solid slab either with or without drop panels. In other words, checking of shear stress at column perimeter in solid slabs is of paramount importance (Narayanan *et al.*, 2000).

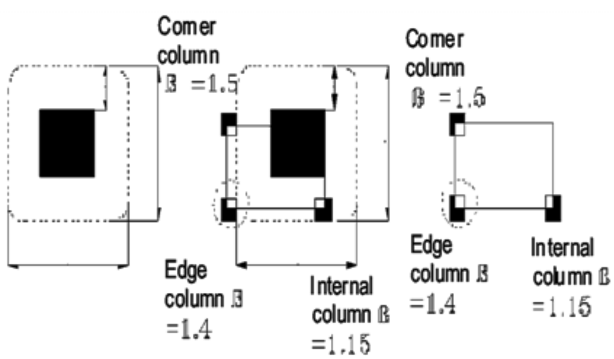

Figure 1: Critical column perimeter

Figure 1 shows the critical perimeter, μ, where there is much higher shear stress concentration at the column face. The critical perimeter plays a role in the determination of RC slab shear, and it is normally within $0.5d$ to $2d$ from the column face. Hence, the maximum design shear stress $v_{Ed,\max}$ is from:

$$v_{Ed,\max} = \frac{\beta_c v_{Ed}}{\mu d} \quad (1)$$

In Equation 1, v_{Ed} is the applied shear stress value at the support, and the moment transfer factor β_c solely depends on the column orientation and position (Figure 1). The appropriate recommended values for β_c are illustrated in that figure, for example. Therefore, the shear resistance capacity for a RC slab, $v_{Rd,c}$, without shear reinforcement is given by Equation 2, and the value of maximum concrete shear resistance, $v_{Rd,\max}$, is also shown in Table 1.

$$v_{Rd,c} = 0.12k(100\rho_1 f_{ck})^{1/3} \geq 0.035k^{1.5} f_{ck} \quad (2)$$

Where $k = 1 + \sqrt{\frac{200}{d}} \leq 2$, and the steel ratio $\rho_1 = \sqrt{\rho_{1x} + \rho_{1z}} \leq 0.02$. For situations where the ρ_1 value exceeds 0.4%, the value is modified by the modifications factor (M) as shown in Table 2.

Table 1: Maximum concrete shear resistance

$f_{ck}(MPa)$	$v_{Rd,\max}$
25	4.05
30	4.75
35	5.42
40	6.05
45	6.64

Table 2: Modification factor

$f_{ck}(MPa)$	M
25	0.94
30	1.02
35	1.05
40	1.10
45	1.14

Punching shear reinforcement steel becomes necessary if $v_{Ed} \succ v_{Rd,c}$, and its provision is very seldom. However, if otherwise, then the slab needs to be re-designed. Hence, in this study, the provisions of shear reinforcement is limited, and more information on the computational guide for punching shear reinforcement for slab designs that requires shear reinforcement are available from literature and related textbooks.

Shear Capacity Violation

This study framework for shear capacity determination is in accordance with the deterministic principle outline in European code (as shown in Figure 2). There is considerable safety if the concrete shear resistance is greater than the applied shear, which is rational. Intuitively failure is unavoidable if otherwise. Hence, the presentation in Figure 2 that shows the shear capacity violation function is shown with the expression in Equation 3.

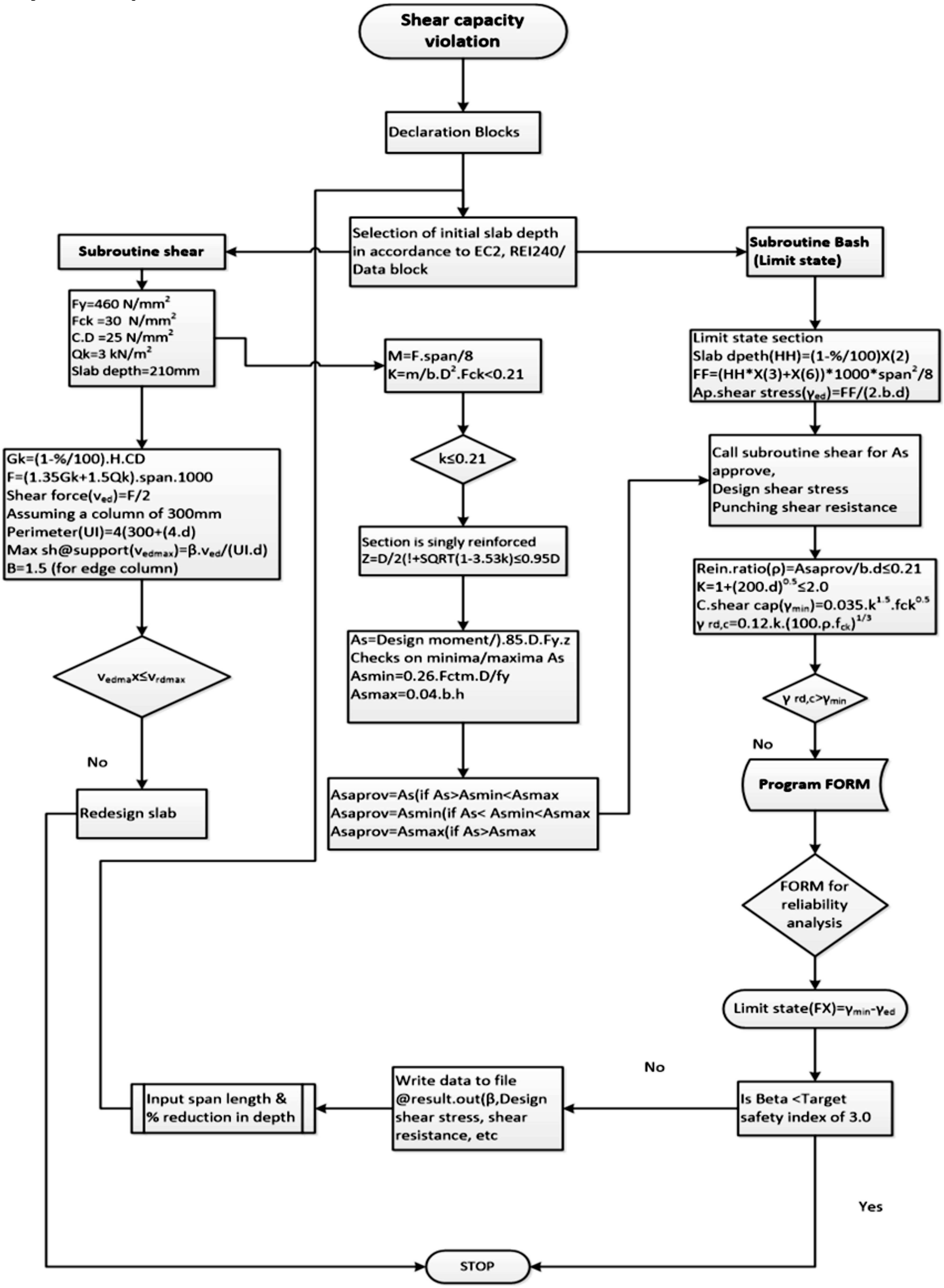

Figure 2: Shear capacity violation

$$g(x)=\begin{cases} v_{Rd,c}-v_{Ed} & (\text{if } v_{Rd,c}\geq v_{\min}) \\ v_{\min}-v_{Ed} & (\text{if } v_{Rd,c}\prec v_{\min}) \end{cases} \quad (3)$$

where $v_{\min}=0.035k^{1.5}f_{ck}$ and $v_{Rd,c}$ is previously given using the expression in Equation 2. Accordingly, the limit state performance function in Equation 3 has five basic stochastic variables, and these include f_{yk} (Normal, 0.03), h (Normal, 0.05), f_{ck} (Log-normal, 0.17), γ_{con} (Normal, 0.03) and q_l (Log-normal, 0.2). The values in the parenthesis shows the statistical distribution type and co-efficient of variation. Hence, modifying the concrete shear capacity limit-state function with shear enhancement factor, λ_{prop}, gives:

$$g(x)=\begin{cases} v_{Rd,c}*\lambda_{prop}-v_{Ed} & (\text{if } v_{Rd,c}\geq v_{\min}) \\ v_{\min}*\lambda_{prop}-v_{Ed} & (\text{if } v_{Rd,c}\prec v_{\min}) \end{cases} \quad (4)$$

Since shear verification for concrete slab without shear reinforcement is characterized by the concrete strength, f_{ck}, and reinforcement ratio, ρ, values (Porco *et al.*, 2013; Vainiūnas *et al.*, 2015), and this work includes the change in span length in addition to the two main influencing factors as mentioned previously.

RESULT AND DISCUSSION

Figure 3 and 4, show the general behaviour for the optimised under different parametric conditions.

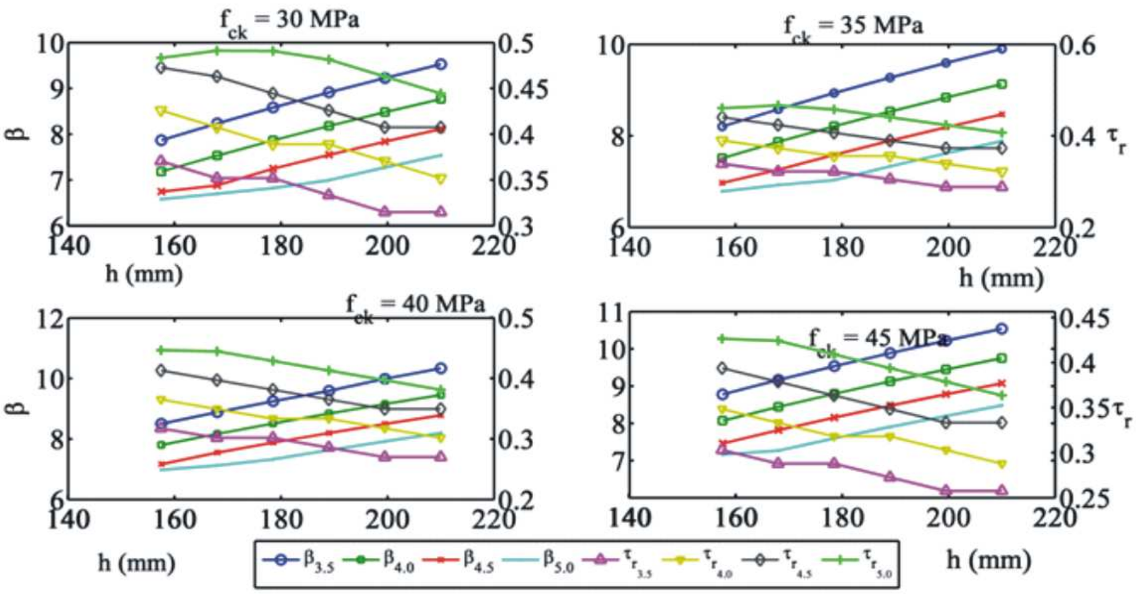

Figure 3: Shear ratio safety performances for the optimised section

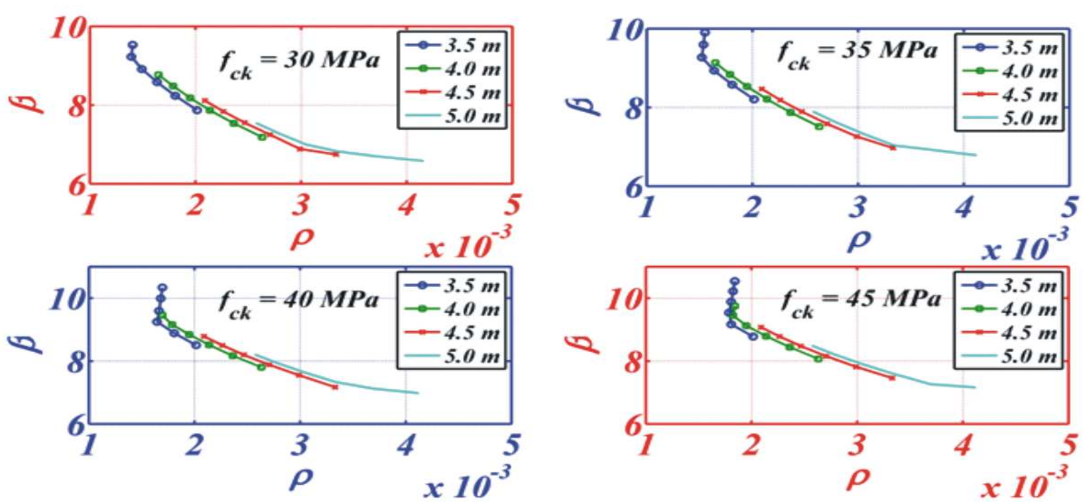

Figure 4: Steel ratio and safety value relationship at different optimised RC design depths

In Figure 3, the safety performance decreases with decreasing thickness, and the longest span shows a lower value compared to other span lengths. However, the ratio of the design shear to the resistance shear or the shear ratio, τ_r, formulation increases with increasing span length. This similar behaviour happens with decreasing slab depth thickness. The behaviour can be attributed to the working load that resulted in a much higher design shear value than the resistance offered by the concrete. Similarly, there is an observed uniform decrease in structural safety value β value as depicted in Figure 4 irrespective of span and concrete strength, f_{ck}, values. This behaviour can also be attributed to the declining shear resistance value. Studies have shown that the effective depth influence on slabs can result in about a 12% decrease in shear resistance capacity (Porco *et al.*, 2013). Hence, this might explain the reported decrease in shear resistance value.

Influencing ρ ***factor***

The longitudinal reinforcement ratio is an influencing factor for concrete slab shear resistance. For this reason EC2 (2008) methodology is adjudged to be precise compared to other code formats like the ACI 318 (2005), which does not evaluate the ρ value even though results from the use of codes other than European code will not result in shear errors (Vainiūnas *et al.*, 2015). The omission of ρ value evaluation by ACI 318-05 is primarily due to its contribution in propagating brittle failure mode (Robert *et al.*, 2013). Critics of the EC2 (2008) approach believe it limits slab strength with low ρ, because of the inclusion of slab depth and flexural reinforcement (Guandalini *et al.*, 2009). A good example is shown in Figure 5, where the load capacity increases with higher reinforcement ratio as shown by the dashed line. The ρ value influence on deterministic shear strength is well documented in literature, specifically works by Muttoni (2008) and Rizk *et al.* (2011). However, its relationship with β is not fully understood; hence, the safety performance of the optimised section is shown in relation to ρ value as depicted in Figure 4.

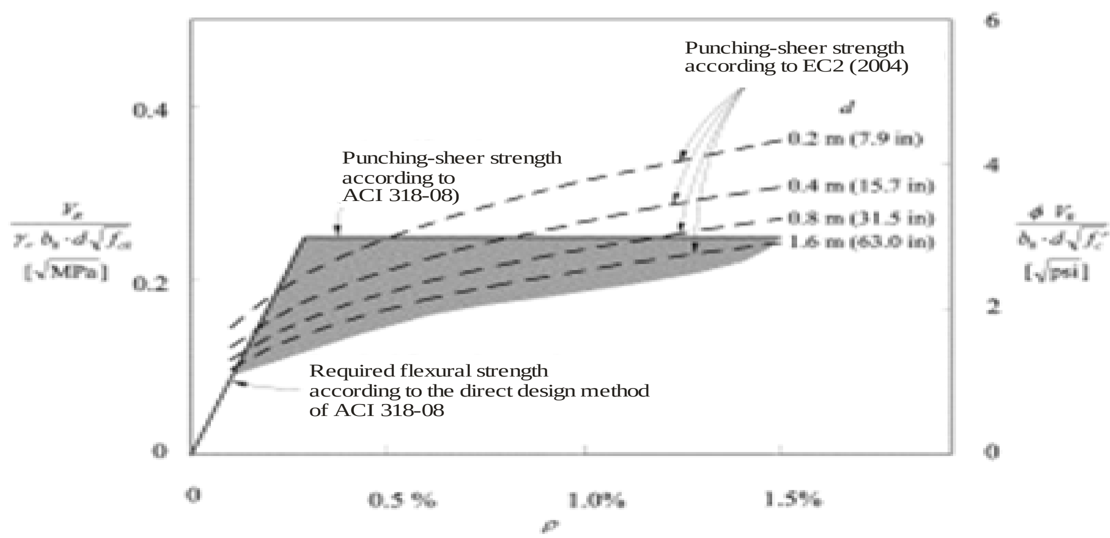

Figure 5: Influence of flexural reinforcement on shear strength: after muttoni (2008)

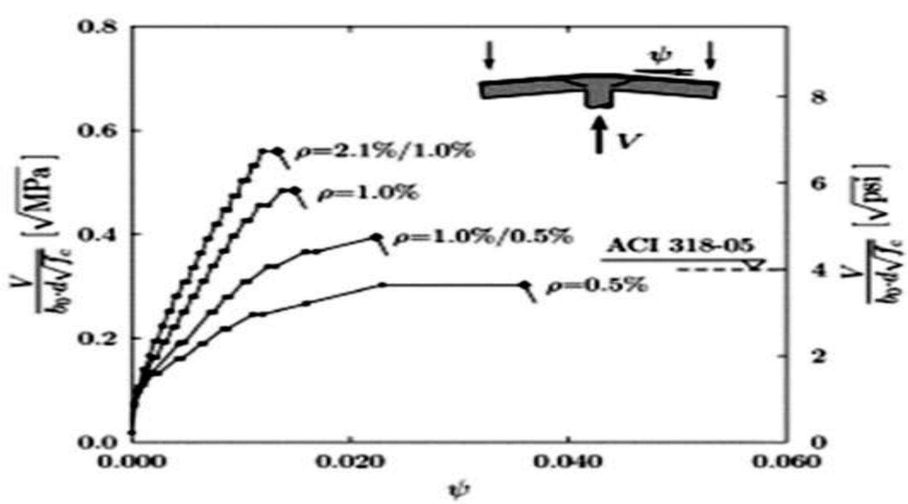

Figure 6: The   limits characterisation: after muttoni (2008)

Figure 4 shows that decreasing the slab depth results in a marginal increase in value, which similarly increases with increasing span length. In general, increasing the value decreases the safety value for the optimised section. Although the safety threshold in terms of flexural failure is not violated, with the decreasing concrete thickness, increasing flexural reinforcement value not necessarily translates into improving concrete shear resistance for the given section. However, studies have shown that higher reinforcement ratios increases shear capacity, but with associated consequences on the deformation requirement (Muttoni, 2008).

A clear distinction for value limits is not clear because of the complex nature of shear capacity. In most cases at lower value, shear failure occurs before yielding of slab when shear strength is lower than the flexural capacity. However, as mentioned previously, brittle failure mode is associated with high value, and this behaviour is depicted in Figure 6. This resulted in the development of several semi-empirical failure criteria. Since then, different adjustments and improvements have been proposed in many scholarly articles.

As a general note, the structural reliability values in shear are much higher than that in flexure; ranging from 6 to 9 on average. Similar values within that range are reported using experimental procedures; the specific values ranges from 6.028 – 8.645 (Vainiūnas *et al.*, 2015). The author attributed the range of the values to the high quality of the production process of specimen, which means low Standard Deviation (SD) values. It is logical to suggest from the findings presented herein that the concrete shear capacity estimate can be enhanced significantly if flexural capacity threshold in failure is to be adopted on minimum for shear capacity violation.

Concrete shear resistance enhancement

Lantsoght, van der Veen, and de Boer (2015) worked on a reliability-based shear expression for shear capacity of RC slabs (bridge deck) under concentrated loads near the support, where an enhancement factor, is sought in achieving the target safety index of 3.6. This value is the required safety level for existing structure under class 3. However, the authors considers the ratio of the experimental test to predicted capacity for the concrete resistance influence, while considering the Limit State Function (LSF) and the use of Monte Carlo simulation rather than the First Order Reliability Method (FORM) according to the Netherlands design requirement. Applying the same principle for the enhancement, but with the use of FORM and the shear estimate requirement to European code formulation, the required is sought herein.

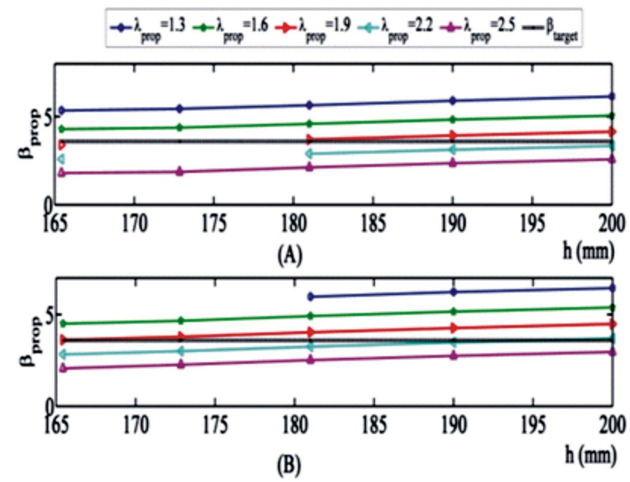

Figure 7: Shear capacity enhancement with two concrete strengths class: (A) 30 MPa (B) 35 MPa

Figure 7 shows the behaviour of the several values in conjunction with the LSF given in Equation 4. Adopting similar literature reliability safety level of 3.6 (for the assessment of class 3 structures) as obtained in Lantsoght, van der Veen, and de Boer (2015) for the basis of comparison. Therefore, in achieving the adopted safety level (the dotted lines in Figure 7 a factors of about 2.0 and 2.2 are found to be associated with the use of concrete strength classes of 30 and 35 MPa, respectively. In comparison to other findings in literature, similar analysis but according to the Netherlands specification, yields 1.78 for the shear enhancement factor (Lantsoght, van der Veen, de Boer, 2015). By implication from the result in Figure 7, the concrete shear resistance capacity can be increased significantly with a factor of 2.0. This shows about 11% improvement on the previous literature finding, and which is substantial enough for adoption.

CONCLUSIONS

Literature survey reveals the underestimation concern in the Eurocode approach for RC slab for concrete shear resistance capacity. The concern mitigation is through the development of performance enhancement schemes employing the probabilistic safety performance to provide improvement measures to the concrete shear resistance function while maintaining an acceptable closed form solution. Shear resistance, factors are introduced to modify the existing limit-state function. The numerical results from design examples result on the implemented limit state performance shows an improvement of about 11% to the design estimation of concrete shear resistance, because the concrete shear capacity can be increased significantly with a shear enhancement factor of 2.0.

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