

Evaluation of TS500-2000 Shear Strength Provisions for Deep Beams

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Abstract: In order to account for the strut action in point loaded deep beams, TS500-2000 allows use of simple shear strength equations instead of more refined models. According to TS500, when the clear span-to-depth ratio, l_n/d is less than 5, the shear strength of deep beams containing both vertical and horizontal shear reinforcement can be calculated by a simple expression which accounts for the effect of web reinforcements along with the clear span-to-depth ratio, l_n/d . In this study, the accuracy and conservativeness of the shear strength equations for deep beams in the TS500-2000 are evaluated. ACI-DAfStb evaluation database of shear tests on point loaded simply supported reinforced concrete members with vertical and horizontal shear reinforcement, is used for this purpose. Based on the results obtained, recommendations are made to improve the accuracy of TS500-2000 sectional shear design equations.

Yüksek Kirişler için TS500-2000 Kayma Dayanımı İlkelerinin Değerlendirilmesi

Anahtar Kelimeler

Yüksek kirişler,
Kayma dayanımı,
TS500-2000,
Kemerlenme etkisi

Özet: TS500-2000 yönetmeliği, tekil yüklü yüksek kirişlerde meydana gelen kemerlenme etkisini hesaba katmak için, daha gelişmiş modeller kullanmak yerine basit kayma dayanımı denklemlerinin kullanılmasına izin verir. TS500'e göre, net açıklığı, faydalı yüksekliğinin 5 katından küçük olan hem dikey hem de yatay kayma donatısı içeren yüksek kirişlerin kayma dayanımı, her iki doğrultudaki kayma donatısının ve net açıklığın faydalı yüksekliğe olan oranının etkisini içeren basit bir kayma dayanımı denklemi ile bulunabilir. Bu çalışmada TS500-2000'deki kayma dayanımı denklemlerinin doğruluğu ve güvenliği değerlendirilmiştir. Bu amaçla, düşey ve yatay kayma donatısı içeren, basit mesnetli ve tekil yüklü betonarme derin kiriş deneylerinden oluşan ACI-DAfStb değerlendirme veritabanı kullanılmıştır. Elde edilen sonuçlara dayanarak, TS500-2000 kayma dayanımı denklemlerinin doğruluğunu geliştirmek için öneriler yapılmıştır.

1. Introduction

In practice, shear design of point loaded non-slender members occurs in the design of pile caps under column loads, transfer girders and thick mat foundations resting on piles. In such non-slender members shear strength is enhanced due to the strut action between the applied load and the support reaction. Thus, sectional models give lower shear strength predictions unless this strut action in deep beams is modeled by strut-and-tie models or non-linear finite element models which accurately account for the flow of forces [1]. A comparative review of different models for shear strength of deep beams can be found in a recent paper by Liu and Mihaylov [2].

TS500 [3] shear design equations for deep beams are basically empirical formulas with little emphasis on the diagonal strut action that occurs in deep beams.

Simple expressions to account for the shear enhancement in deep beams are present in many design codes. Eurocode 2 [4] and the *fib* Model Code 2010 [5] allow use of empirical sectional shear strength equations that account for shear enhancement in deep beams instead of more refined models.

To better understand the accuracy of TS500 [3] shear design equations for deep beams, experimental shear failure loads of members with horizontal and vertical stirrups under point loads are compared to predicted strengths. To evaluate the shear design provisions of TS500 [3], the ACI-DAfStb database of shear tests on

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simply supported point loaded reinforced concrete members is considered [6]. Shear strength of members in this evaluation database are compared to the TS500 shear strength predictions. Based on this comparison, it was concluded that the TS500 shear strength equations for deep beams give overly conservative predictions for point loaded members. A shear enhancement method, similar to the shear enhancement method in BS8110 [7], is proposed for point loaded deep beams. It is shown that the accuracy of shear strength predictions increases if the proposed shear enhancement method is used when calculating the shear strength of non-slender point loaded members.

2. Shear Design Provisions of TS500-2000 for Deep Beams

According to TS500 [3] deep beams are defined as beams where the clear span to effective depth ratio $l_n/d < 5$ (Figure 1). Design shear force is calculated at a distance $a/2$ away from the face of support which cannot be taken greater than the effective depth, d . The distance a is defined as the distance from the applied point load to the face of support.

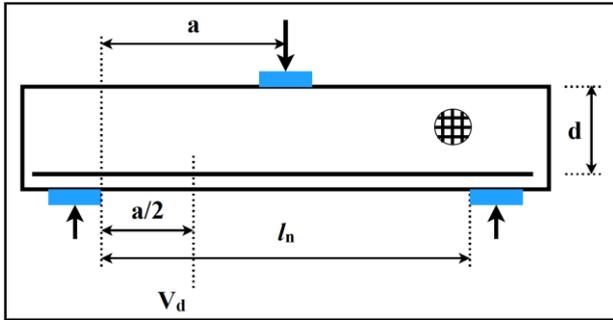


Figure 1. Simply supported deep beam under three-point loading

Section size must be increased if the design shear force, V_d is greater than

$$\text{for } \frac{l_n}{d} < 2 \quad V_d \geq 0.2f_{ctd}b_w d \quad (1a)$$

$$\text{for } 2 \leq \frac{l_n}{d} < 5 \quad V_d \geq 0.017f_{ctd}b_w d(10 + \frac{l_n}{d}) \quad (1b)$$

Contribution of concrete to the shear strength of beams subjected to no axial load, V_c is calculated as

$$V_c = 0.8V_{cr} \quad (2a)$$

$$V_{cr} = 0.65f_{ctd}b_w d \quad (2b)$$

where f_{ctd} is the factored tensile strength of concrete and can be calculated as,

$$f_{ctd} = \frac{0.35\sqrt{f_{ck}}}{\gamma_c} \quad (3)$$

In Eq. (3) f_{ck} is the characteristic compressive strength of concrete and γ_c is the partial safety factor for concrete.

Shear strength provided by horizontal and vertical shear reinforcement is calculated as

$$V_w = \frac{d}{12} \left[\left(1 + \frac{l_n}{d}\right) \frac{A_v f_{ywd}}{s} + \left(11 - \frac{l_n}{d}\right) \frac{A_{vh} f_{yd}}{s_h} \right] \quad (4)$$

In the above equation A_v is the area of vertical stirrups with a spacing of s and A_{vh} is the area of horizontal reinforcement placed over the height of the deep beam at a spacing of s_h . The minimum horizontal and vertical reinforcement are given as,

$$\frac{A_v}{s} \geq 0.8 \frac{f_{ctd}}{f_{ywd}} b_w \quad (5a)$$

$$\frac{A_{vh}}{s_h} \geq 0.8 \frac{f_{ctd}}{f_{ywd}} b_w \quad (5b)$$

The shear strength of a deep beam can then be calculated as follows:

$$V_r = V_c + V_w \quad (6)$$

The horizontal and vertical shear reinforcement should be detailed such that the spacing of these reinforcements should not exceed minimum of $d/5$ or 400 mm.

3. Shear Strength Predictions Using TS500-2000 Provisions

Shear strength predictions of the tests in the evaluation database are calculated according to the shear enhancement method in TS500-2000. Partial safety factors for concrete, γ_c , and steel reinforcement, γ_s , are taken as 1.0 when calculating strength predictions of the specimens in the database. When calculating the shear resistance of deep beams using TS500 shear design provisions, f_{ck} characteristic concrete strength is taken as $f_{cm} - 1$ MPa as suggested in TS500, where f_{cm} is the reported average concrete strength of the test specimens in the evaluation database. Failure loads that include the shear due to self-weight of the specimens and weight of loading equipment are considered. When calculating the shear strength of deep beams, the lengths of support and loading plates are needed, therefore an average value of $0.2h$ is assumed as suggested in Reineck and Todisco [8], if plate sizes are not given in relevant literature.

Details of ACI-DAfStb evaluation database of shear tests on non-slender members with vertical and horizontal shear reinforcement are presented in a recent paper by Todisco et al. [6]. This database

consists of 89 tests after applying several selection criteria as explained in Reineck and Todisco [8].

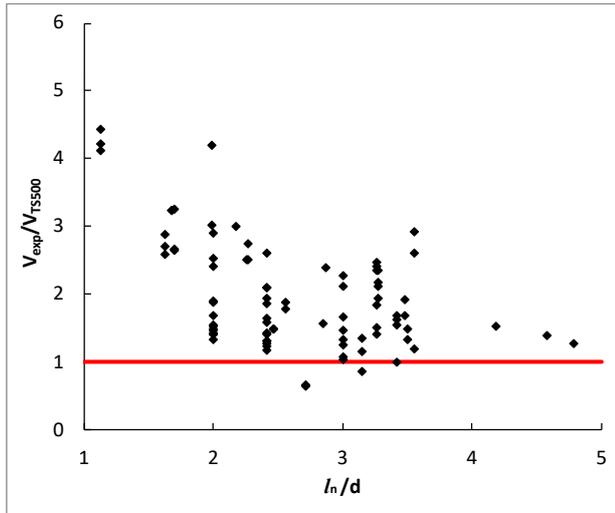


Figure 2. Comparison of experimental values to shear strength predictions by TS500-2000 [3]

Figure 2 compares the shear strength predictions by TS500-2000 [2]. The ratio of experimental shear strength to predicted shear strength for each test is plotted with respect to clear span-to-effective depth ratio, l_n/d .

As can be seen from Figure 2, the sectional shear enhancement method given in TS500 gives very conservative predictions especially for very short specimens. The mean ratio of experimental-to-predicted shear strengths is 2.01 with a coefficient of variation of 39% which indicates a quite high scatter if the shear design equations for deep beams in TS500 are considered for non-slender members.

Although the method considers the presence of horizontal reinforcement, predictions are still overly conservative for many of the beams. In Eq (4) contributions of horizontal and vertical reinforcement to the shear strength are taken into account using multipliers with little physical meaning. Several researchers [9-11] observed that horizontal web reinforcement contributes more effectively to the shear strength than vertical web reinforcement when shear span-to-depth ratio a/d is less than about 0.75 since horizontal web reinforcement is aligned more favorably to resist the transverse tension in the struts [12]. On the other hand, vertical web reinforcement contributes more effectively to the shear strength than horizontal web reinforcement when shear span-to-depth ratios are greater than or approximately equal to 1. The calculations indicated that predicted shear strength provided by horizontal web reinforcement formed about 70% of the total shear strength provided by steel even for deep beams with shear span-to-depth ratios that are greater than or approximately equal to 1.

4. Proposed Method for Shear Strength Predictions of Deep Beams

It is clear from Figure 2 that the shear strength equations adopted in TS500-2000 [3] give very conservative results particularly for beams with low clear span-to-effective depth, l_n/d ratios. Simple expressions to account for the shear enhancement in deep beams are present in many design codes. Vollum and Fang [13-14] compared shear enhancement methods of *fib* Model Code 2010 [5], Eurocode 2 [4] and the previous UK code BS8110 [7] for simply supported beams under multiple point loads close to supports. Eurocode 2 and *fib* Model Code 2010 consider shear enhancement when loads are applied within $2d$ of supports and reduce the design shear force by a factor. The UK design code BS8110 [7] takes a different approach and increases the shear resistance provided by concrete. Based on their findings, the BS8110 shear enhancement method gives significantly better strength predictions than Eurocode 2 [4] and the *fib* Model Code [5], particularly for beams with multiple loads.

In this paper, a shear enhancement method is proposed to increase the accuracy of the TS500 predictions. It is important to recall that the sectional shear enhancement method is merely an empirical approach to consider the increase in shear capacity of deep beams, without applying more detailed models to study the flow of forces when loads are applied closer to supports.

For non-slender members without shear reinforcement the enhanced shear capacity is a result of the strut action that forms between the load and the support reaction. The capacity of this strut depends mainly on the concrete strength. Therefore, it is suggested that the enhanced shear capacity in deep beams can simply be calculated by increasing the shear strength provided by concrete, V_c , by a factor of $(5d/l_n)$ similar to the approach taken in BS8110 [7]. The enhanced shear capacity can be calculated as,

$$V_{c,enhanced} = \frac{5d}{l_n} V_c \quad (7)$$

where $5d/l_n$ cannot be greater than 2. Similar to the shear strength equations in other design codes that account for the shear enhancement in deep beams, shear strength provided by reinforcement is simply calculated using the well-known shear design equation which only accounts for the shear capacity provided by the vertical shear reinforcement

$$V_w = \frac{A_v}{s} f_{yw} d \quad (8)$$

As can be understood from Eq. 7, only the shear capacity provided by concrete is increased if loads are applied within distance $2.5d$ of the supports of deep beams with vertical and horizontal shear reinforcement. It must be noted that in other design codes [4,5,7] where shear enhancement is accounted for by using simple empirical expressions, the shear strength provided by shear reinforcement is simply calculated using the shear design equation which only accounts for the shear capacity provided by the vertical shear reinforcement and the strut action is accounted for by increasing only the contribution of concrete to the shear strength.

In case of non-slender members with shear reinforcement the enhanced capacity cannot exceed the strength given by crushing of struts, $V_{r,max}$ as defined in Eq (1). It is proposed that the enhanced shear capacity for non-slender members with shear reinforcement can be calculated as follows

$$V_r = V_{c,enhanced} + V_w \quad (9)$$

where $V_{c,enhanced}$ and V_w are calculated as in Eq. (7) and Eq. (8), respectively.

5. Shear Strength Predictions using the Proposed Method

Shear strength predictions of specimens in the evaluation database, using the proposed shear enhancement method, resulted in an average value of experimental to predicted ratio of 1.64 and a coefficient of variation that equals to 24%. Figure 3 compares the experimental shear strengths to predicted shear strengths in the two databases using the proposed shear enhancement method. It is clearly seen from Figure 3 that the proposed shear enhancement method yields better results with less scatter.

Table 1 gives the overall statistical evaluation of the two enhancement methods. The statistical results show that the shear enhancement method proposed in this paper, gives better predictions of the experiments in the database.

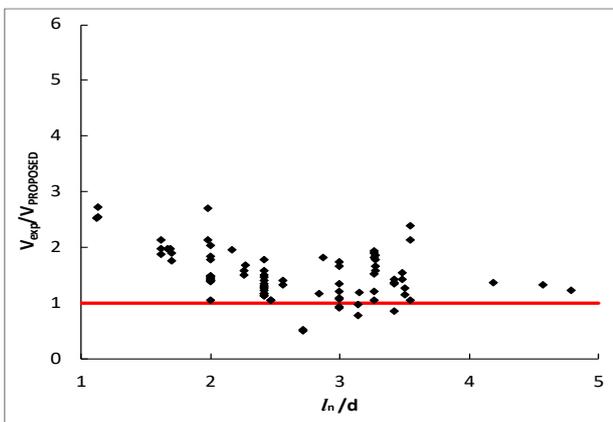


Figure 3. Comparison of experimental values to shear strength predictions by the proposed method

It is important to mention that there is less data scatter with much better coefficient of variation. There are only 4 non-conservative predictions out of 89 tests, that is shear prediction by the proposed method, $V_{PROPOSED}$ is greater than the experimental shear strength, V_{exp} . Experimental to predicted shear strength ratios of 4 non-conservative predictions ranged from 0.92 to 0.80. It must be noted that the number of nonconservative results is less than the 5% fractile which is acceptable according to many design codes [6]. It is also important to note that these non-conservative predictions are for large members with effective depths greater than 600 mm and no other distinct trend is observed.

Table 1. Statistical analysis of experimental to predicted shear strength ratios

Statistical Values	V_{exp}/V_{TS500}	$V_{exp}/V_{PROPOSED}$
Mean	2.01	1.64
Maximum	4.43	2.87
Minimum	0.87	0.80
CoV, %	39	24

Since the predominant failure mode of deep beams is shear failure rather than flexural failure, shear design of deep beams under seismic loading must be carried out with utmost care. Recent Turkish Earthquake Code [15] states that the concrete contribution to shear strength shall be taken as zero if the shear force due to only earthquake loading is greater than half of the shear force obtained from a load combination which includes both gravity and earthquake loading.

6. Conclusion

In the shear design of deep beams Turkish design code TS500-2000 [3] allows the engineer to use simple sectional shear strength equations which consider the effect of vertical and horizontal shear reinforcement instead of using more refined models to account for the strut action in non-slender members. In order to assess the conservativeness and accuracy of the shear design equations in TS500, shear strength predictions are evaluated using ACI-DAfStb database for shear tests on non-slender reinforced concrete members with horizontal and vertical shear reinforcement [6]. It is shown that the shear strength equations given in TS500 yield very conservative results especially for short members. In this paper, a simple shear enhancement method is proposed to increase the accuracy of the shear strength predictions of non-slender members. It is shown that the proposed shear enhancement method, along with the TS500 shear provisions, gives better shear strength predictions for non-slender members with horizontal and vertical shear reinforcement and could be taken into consideration in any future adjustments to code provisions. On the other hand, if the deep beam in consideration is part of the lateral load resisting system, the shear design of the deep beam must be carried out according to the recent Turkish Building Earthquake Code [15].

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