Effect of orientation of stirrups in combination with shear span to depth ratio on shear capacity of RC beams

Chalachew B. Hunegnawa,*, Temesgen W. Aure

ARTICLE INFO

Keywords:
Orientation of stirrups
Shear-span-to-depth ratio
Shear capacity of RC beams
Concrete compressive strength
Diagonal splitting

ABSTRACT

The shear behavior of reinforced concrete (RC) beams has been a major research area for a long time. Since the shear response of RC beams is affected by different factors, many researchers have reported that the nature of shear behavior is complicated. One of these factors worth investigating is the inclination of shear reinforcements. This paper investigated the effect of the orientation of stirrups on the shear capacity of RC beams as the shear-span-to-depth ratio (a/d) varies. The contribution of concrete compressive strength was also studied. An experimental program investigating 21 RC beams has been conducted. The test results revealed that the shear capacity increases as the arrangement of stirrup changes from conventional vertical arrangement to inclined arrangement. However, the increment is high in beams with (a/d) ratio of 2.2 than beams with (a/d) ratio of 2.6, which are relatively slender. Shear capacity also increases as concrete compressive strength increase, which shows that concrete contribution to the shear capacity of beams should be taken into account.

In addition to the experimental test, the beams were analyzed numerically by using a general-purpose finite element package, Abaqus. The shear capacity of reinforced concrete beams obtained from the numerical analysis is in a good agreement with the experimental result. The results obtained by numerical analysis and experimental tests are compared to analytically calculated values by using shear provisions of ACI 318-14 and EN-2. Both ACI 318-14 and EN-2 are generally conservative in predicting the shear capacity of RC beams. However, the conservativeness of these codes reduced as a/d ratio of the beams increase.

1. Introduction

Generally reinforced concrete beams are designed to resist primarily flexure and shear. Thus, the section must be checked for resistance to shear failure (diagonal tension) and should be provided with stirrups when the unreinforced concrete section is not adequate for shear. The shear behavior of reinforced concrete (RC) beams is complex. It is due to its non-homogeneity, presence of cracks and reinforcement, and the non-linearity of material response. The manner in which shear failure occurs varies widely with the geometry, loading, and material properties. In reinforced concrete beams, the exact distribution of shear stresses across the depth of the cross-section is not well known.

Moayyad and Naiem (2013) studied the effect of inclined stirrups on the shear strength of RC beams by using swimmer bars as shear reinforcement. The results from this study revealed that beams with an inclined arrangement of bars perform better than beams with conventional vertical bars in resisting shear. The width and length of the cracks observed were less in beams with swimmer bars.

On the other hand, Sayyad et al. (2013) investigated the effect of the orientation of stirrups on the flexural capacity of deep beams. They conducted an experimental study on beams with stirrups arranged laterally (horizontally) and beams with stirrups inclined by 45° about the beam axis. They compared the experimental results with the response of deep beams having vertical shear links. The result shows that the load-carrying capacity of deep beams with lateral (horizontal) stirrups is higher than that of beams with inclined and vertical shear links. The investigation also indicated that lateral and inclined stirrups resist shear cracks more effectively than vertical stirrups. Studies also showed that one of the most crucial factors that affect the shear capacity of beams is the shear-span-to-depth ratio. An experimental study conducted by Slowik (2014) indicated that the diagonal shear failure is affected by the size of the beams. According to this study, the shear span-to-depth ratio affects the shear failure process in reinforced concrete beams.
The new Ethiopian Building Code, which is derived from European Norm, uses variable strut inclination angles. However, according to Grandi et al. (2015), applying invariable compression strut inclination values for a simplified model of shear resistance satisfies the safety requirements. The variable strut angle can be used, as the case in EN-2 (2004) and also in Ethiopian Building Code, keeping in mind that the shear resistance limit by crushing of compressive struts is the most conservative approach. It also requires careful selection of the lower bound strut inclination angle while using EN-2 (2004). This is due to low inclination angle tends to widen the diagonal crack which in turn reduces shear resistance of compression struts.

Most codes assume that shear cracks occur in the web with an angle $\theta$ of about 45° and recommend that an inclined stirrup arrangement with an angle of inclination of 45° with the longitudinal axis of the beams is the most effective arrangement. During using the variable strut angle shear model, a limited compression strut angle range of 45° to 21.8° shall be used. (CEN (European Committee for Standardization), 2004; Ethiopian Standards Agency, 2015)

2. Problem statement

Different codes of practice have no common shear provisions in considering many factors affecting shear strength. Experimental tests are required to investigate the accuracy of different shear models in predicting the actual shear capacity of RC beams.

Moreover, different studies have indicated that beams with inclined arrangement of stirrups perform better in resisting shear than beams with the conventional vertical arrangement. However, existing studies do not show how effective is a specific inclined arrangement of stirrup for various range of a/d ratios.

3. Objectives

The main objective of this study is to investigate the effect of the orientation of stirrups in beams with different ranges of a/d ratios and to examine the contribution of concrete compressive strength on the shear capacity of reinforced concrete beams.

Specific objectives are:

- To evaluate the code provisions which are currently in practice in predicting the shear capacity of RC beams.
- To examine the ability of FEM in accounting effect of factors like arrangement of stirrups, shear span to depth ratio, and concrete compressive strength on the shear capacity of RC beams.

4. Methodology

The methodology adapted in this study is an experimental test in combination with numerical analysis. We used general-purpose finite element software called ABAQUS and analytical calculations by using semi-empirical provisions of ACI-318 and EN-2.

4.1. Experimental program

An experimental test was conducted on 21 beam specimens. The detail properties of the test specimens are presented in Table 1. The specimens were fabricated from concrete mix having aggregate with a maximum size of 25mm, sand, and Portland cement.

In all specimens, 10 mm diameter bars are used as longitudinal reinforcement and 6mm diameter plain bars as shear reinforcement. Tensile test was conducted on both longitudinal and shear reinforcement steels to determine the yield and ultimate strengths. Table 2 presents the mechanical properties of steel reinforcements used in this experimental program.

The procedures followed in the experimental program included: (i) preparation of reinforcement cage, (ii) casting of the beams and curing for 28 days, and (iii) conducting experimental test at the end of the 28th day of curing period. The test was conducted by using a three-point loading Universal Testing Machine (UTM).

The beam identifications in Table 1 is: B stands for beam, the number that follows is group number given based on concrete grade (1 stand for a beam cast from concrete with compressive strength of 28.8 MPa and 2 stand for a beam cast from concrete with compressive strength of 37.2 MPa), L stands for the shear link and the number that follows it is inclination angle of the links with the beam axis. The number that follows the inclination angle stands for the shear-span-to-depth ratio. For example, the beam B1L-90-2.6 refers to a specimen cast from concrete with cube compressive strength of 28.8 MPa, link with an angle of 90° (vertical) about the beam axis, and shear span-to-depth ratio of 2.6. Figure 1 shows the reinforcement arrangement and cast beam ready for a test. Beams with the shear span-to-depth ratios of 2.2 and 2.6 are selected for this study based on the laboratory setup available and to ensure that the beams fail by shear failure mode.

4.2. Finite element modeling

A 3D nonlinear finite element model was developed to investigate the shear behavior of RC beams by using the commercial package, Abaqus 6.13. This is a general-purpose analysis software that can solve linear and
nonlinear problems. The beams modeled for FE analysis had the same property as that of the respective experimental specimens.

4.2.1. Geometry model

The concrete section was modeled with eight-node linear brick elements with a reduced integration point (C3D8R). The shape function of this element is the same as the eight-node brick element with full integration (C3D8). C3D8R is advantageous over C3D8 because, in C3D8R, the locking phenomena observed in C3D8 do not occur due to the reduced integration point. The reinforcement was modeled by using T3D2 elements, which are linear truss elements. The reinforcement cage was connected to the surrounding concrete using embedded region constraint found in Abaqus. This allows each node in the reinforcement element to connect to the nearest concrete node.

4.2.2. Loading and boundary conditions

The beams were modeled as simply supported with a center to center span of 650mm and 550mm for a group of beams with a shear span-to-depth ratio of 2.6 and 2.2, respectively. A discrete rigid plate is provided at the supports and loading point to replicate the experimental test and to prevent stress concentration (Figure 2.). To capture the behavior of the beams after peak load, a displacement-controlled load was applied. The displacement load was applied in the direction of gravity at the center of the loading plate.

4.2.3. Material model

4.2.3.1. Concrete. The material constitutive behavior of concrete is nonlinear and complex. However, finite element packages can model these complex behaviors. ABAQUS software provides the capability of simulating damage using either of the three crack models for RC elements: (1) smeared crack concrete model, (2) brittle crack concrete model, and (3) concrete damaged plasticity models. All the three models can be used for reinforced concrete. The CDP model was applied in this study as this technique can represent complete inelastic behavior of concrete both in tension and compression including damage characteristics. It provides a general capability of modeling concrete and other quasi-brittle materials in all types of structures. The concrete damaged plasticity model uses concepts of isotropic damaged elasticity in combination with isotropic tensile and compressive plasticity to represent the inelastic behavior of concrete. The CDP model considers tensile cracking and compressive crushing as the two failure modes of concrete. In this model, the uniaxial tensile and the compressive behaviors are characterized by damaged plasticity.

4.2.3.2. Numerical model for tensile behavior of concrete. The tensile behavior of concrete was modeled by stress-cracking displacement accounting for tension stiffening, strain softening, and concrete-reinforcement interaction. Tension stiffening can either be defined in
Abaqus as a post-failure stress-strain curve or by applying a fracture energy criterion in terms of post-failure stress and cracking displacement. In this study tension stiffening or the unloading portion of the tensile behavior of the concrete is defined by fracture energy criteria in terms of post-failure stress and cracking displacement \( u_{ck} \). In order to obtain this behavior, young’s modulus \( (E_0) \), tensile stress \( (\sigma_t) \), cracking displacement \( \epsilon_c \) values and the damage parameter \( (d_t) \) values were defined.

Abaqus converts the cracking displacement; \( u^c \) to plastic displacement \( u_{pl} \) using Eq. (1) (Smith, 2009).

\[
u^c = u_{pl} - \frac{d_t}{(1 - d_t)} \frac{\sigma_t l}{E_0}
\]

where the specimen length, \( l_0 \), is assumed to be one unit length, \( l_0 = 1 \) and \( d_t \) is concrete tension damage parameter.

4.2.3.3. Numerical model for compressive behavior of concrete. Compressive behavior or the unloading portion of the compressive stress-strain curve is defined by its post-failure stress and inelastic (crushing) strain, \( \epsilon_{cr}^s \). The inelastic is obtained by using the following equation (Smith, 2009).

\[
\epsilon_{el}^c = \epsilon_c - \epsilon_{el}^d
\]

where, \( \epsilon_{el}^d = \frac{\sigma}{E_c} \) is the elastic strain corresponding to undamaged material and \( \epsilon_c \) is the total strain.

Abaqus converts the inelastic strain, \( \epsilon_{el}^c \) to plastic strain \( \epsilon_{pl}^c \) by using Eq. (3).

\[
\epsilon_{pl}^c = \epsilon_{pl}^n - \frac{d_t}{(1 - d_t)} \frac{\sigma_c}{E_0}
\]

where, \( d_t \) is the concrete compressive damage parameter.

4.2.3.4. Reinforcement steel. Abaqus has an option to define reinforcement in concrete as rebars, which is a one-dimensional element embedded in a concrete section. The metal plasticity model is used to describe the behavior of this element and is superposed on a mesh of C3D8R elements used to model the concrete, (Smith, 2009).

This approach allows defining the concrete property independent of the embedded rebar. Rebar-concrete interaction effects like slip-bond and dowel action were modeled using the tension stiffening parameter to model the load transfer mechanism across cracks through the rebar. The behavior of steel used for nonlinear numerical analysis of the RC beams is elastic perfectly plastic.

5. Results and discussion

5.1. Test results

All RC beams tested (21 in number) had identical cross-sectional dimensions and flexural reinforcement ratio. Three parameters were studied in the experimental program: a) inclination of stirrups (90-degree, 67-degree, and 45-degree with the longitudinal axis); b) concrete compressive strength (28.8 MPa and 37.2 MPa); and c) shear span to depth ratio (2.2 and 2.6).

The experimental results are summarized in Table 3 and the sample beam failure mode in Figure 3. The failure mode observed for all the specimens is a diagonal splitting failure (diagonal tension failure) that occurred by crack propagation initially towards the loading point and then towards the support.

The load-displacement response of tested beams (Figure 4) is used to describe the effect of stirrup inclination, shear span to depth ratio, and concrete compressive strength on the shear capacity of beams. The maximum shear capacity of beams obtained from the experimental results is presented in Table 3 for the three cases of stirrup inclination. The shear capacity of beams has increased as the arrangement of stirrups changes from conventional vertical to an inclined arrangement with an angle of inclination of 45°.

Figure 4(a) shows the load-displacement graph of a group of beams with a shear span-to-depth ratio of 2.2 and with the varying arrangement of stirrups. The shear capacity of the beams generally increased as the arrangement of stirrups changed from a conventional vertical to a 45° inclined arrangement. The increment is 16.38% and 24.52% as we go from beams with vertical to 67° and 45° inclined stirrups, respectively. This increase in shear capacity in the case of beams with inclined stirrups could be due to the change in how the bars interact with the path of critical diagonal crack. Inclined bars are arranged in a manner that the direction of diagonal tension stress overlaps with the links.
longitudinally increasing effective shear area. Inclined shear links are also better in restraining the critical diagonal crack opening and in confining the concrete compression struts between cracks than the vertical links. The other reason could be for beams with vertical conventional reinforcement the strains at peak resistance are much less than the yield strain. Hu and Wu (2018) study found that the vertical reinforcement bars in beams are not fully involved in resisting shear compared to that of inclined reinforcement bars.

Figure 4. Load-displacement curve with varying: (a) arrangement of stirrups; (b) concrete compressive strength; (c) shear span-to-depth ratio.
The result in Table 3 shows that the effectiveness of a given orientation of stirrups depends on the a/d ratio. This shows that there exists a correlation effect of a/d ratio and the inclination of stirrups on the shear capacity of beams. In the case of beams with an a/d ratio of 2.2, there is 24.52% increment in shear capacity due to the change in the type of stirrups from conventional vertical to 45° inclined arrangement. However, in the case of beams with a/d ratio of 2.6, the increase in shear capacity is 17.48%. This clearly shows that the effectiveness of the inclined arrangement of stirrups reduces as beams become more slender as shown in Figure 5. It explains that the shear crack propagation and inclination vary as the shear span-to-depth ratio of the beam changes. When we observe the shear capacity difference between the 67° and 45° inclined arrangement, the increase is 7% in the case of beams with a/d ratio of 2.2. However, the increment has reduced to 0.6% for beams with a/d ratio of 2.6, which is an insignificant value. The experimental result revealed that the rate of increase in shear capacity as the orientation of stirrups changes from vertical to inclined arrangement is high in beams with a lower a/d ratio. Thus, the contribution of conventional vertical shear reinforcement to the shear resistance of beams (Vc) decreases as the shear span-to-depth ratio of beams reduces. Based on this, it can be concluded that if shear reinforcement is required to be provided for beams with a smaller shear span-to-depth ratio, it is better to provide in an inclined arrangement.

Figure 4(b) shows that the shear capacity of the specimens increased as concrete grade increases. The increment in shear capacity is 7% as the compressive strength of concrete increases from 28.8 MPa to 37.2 MPa. Therefore, the shear models such as the Eurocode neglects a significant shear resistance i.e. concrete contribution leading to the conservative shear design, especially in beams with a smaller a/d ratio. When the member is reinforced with shear stirrups, the shear capacity should be taken as the combination of strength of concrete without shear reinforcement, Vc and resistance provided by shear reinforcement, Vs (ACI Committee 318, 2014). Furthermore, the load-displacement graph clearly shows that beams cast from 37.2MPa compressive strength concrete fail in a brittle manner compared to beams with 28.8 MPa concrete. Figure 4(c) indicates that as the shear span-to-depth ratio of beam specimen with 45° inclined shear reinforcement changes from 2.6 to 2.2, the shear capacity increases. Generally shear capacity of all groups of beams tested increases with a decrease in shear span-to-depth ratio. But, the increment of shear capacity due to the reduction in a/d varies with the arrangement of reinforcements. As a/d decreases from 2.6 to 2.2, the increase in shear capacity is 4.2% and 10.4% for beams with conventional vertical and with 45° inclined stirrups, respectively (see Table 3). This result indicates that vertical shear reinforcement has a minor influence on the shear capacity of beams as a/d ratio reduces. This result is also consistent with Hu and Wu (2018). This could be due to the fact that in beams with a small a/d ratio, a large portion of shear tends to transfer directly from the loading point to supports via diagonal concrete compression struts. The increase in shear capacity as a/d of beams changes from 2.6 to 2.2 might also be due to the reason that concrete shear capacity due to interlocking and friction (Vc) is higher in RC beams with smaller shear span-to-depth ratio.

5.2. Comparison of test and FEM results

Figure 6 shows the load-deflection graphs obtained from finite element analysis of beams with 45° inclined stirrups, along with experimentally obtained load-deflection results. The results show a good agreement with the experimental data in terms of the ultimate shear capacity. However, the FE response shows high initial stiffness as compared to the experimental results. The possible reasons for the difference in stiffness in case of experimental results and numerical results are; pre-cracking of specimens in case of tests, Uncontrolled Support movements, and difficulty to satisfy the same boundary conditions for FE simulations and tests, and Initial imperfections in case of experimental tests.
The two widely used shear models, ACI 318-14 and EN 2 are evaluated against experimental and FEM results. The shear resistance of the beams calculated using ACI 318-14 and EN 2 shear models are compared to results obtained from experimental tests and numerical analysis. The ratio of experimental results to results obtained by using code provisions and FEM are shown in Table 4 and Figure 7. The results clearly show that there is a good agreement between the experimental results and FEM results. The ratio of experimental results to FEM results is within the

Table 4. Comparison of experimental, numerical and analytical results.

| Beam ID   | a/d  | \( f_{ck} \) | Link angle | Ultimate load (kN) | V\(_{EXP}\) | V\(_{FEM}\) | V\(_{ACI}\) | V\(_{EN}\) | Experimental | FEM   | Analytical |
|-----------|------|--------------|-------------|---------------------|----------|----------|----------|----------|--------------|-------|------------|
|           |      |              |             |                     | V\(_{EXP}\) | V\(_{FEM}\) | V\(_{ACI}\) | V\(_{EN}\) | V\(_{EXP}\)/V\(_{FEM}\) | V\(_{EXP}\)/V\(_{ACI}\) | V\(_{EXP}\)/V\(_{EN}\) |
| B1L-90-2.6| 2.6  | 28.8         | 90          | 48.5                | 52.64    | 24.95    | 32.73    | 0.92     | 1.94         | 1.48  |
| B1L-67-2.6| 2.6  | 28.8         | 67          | 56.62               | 51.4    | 27.39    | 33.91    | 1.1      | 2.06         | 1.66  |
| B1L-45-2.6| 2.6  | 28.8         | 45          | 56.98               | 54.66   | 28.17    | 32.58    | 1.04     | 2.02         | 1.74  |
| B1L-90-2.2| 2.2  | 28.8         | 90          | 50.54               | 53.00   | 24.95    | 30.89    | 0.95     | 2.02         | 1.63  |
| B1L-67-2.2| 2.2  | 28.8         | 67          | 58.82               | 59.25   | 27.39    | 32.22    | 0.99     | 2.14         | 1.82  |
| B1L-45-2.2| 2.2  | 28.8         | 45          | 63.26               | 64.14   | 28.17    | 31.28    | 0.98     | 2.24         | 2.02  |
| B2L-90-2.2| 2.2  | 37.2         | 90          | 54.13               | 52.40   | 27.29    | 32.45    | 1.03     | 1.98         | 1.66  |

Figure 7. Comparison of code predictions and FEM results with experimental results: (a) for various arrangements of stirrups, (b) for varying concrete compressive strength.

5.3. Comparison of test results with existing code models

The two widely used shear models, ACI 318-14 and EN 2 are evaluated against experimental and FEM results. The shear resistance of the beams calculated using ACI 318-14 and EN 2 shear models are compared to results obtained from experimental tests and numerical analysis. The ratio of experimental results to results obtained by using code provisions and FEM are shown in Table 4 and Figure 7. The results clearly show that there is a good agreement between the experimental results and FEM results. The ratio of experimental results to FEM results is within the
range of 0.92–1.1. The ratio of shear capacity determined by the experiment to the shear capacity obtained by using ACI shear provision shows a wide deviation. It is within the range of 1.94–2.14.

In the same way, the ratio of experimentally determined ultimate shear to predicted by using Euro code-2 provision varies from 1.48 in the case of beams with vertical stirrups and shear span to depth ratio of 2.6 to 2.02 in the case of beams with 45-degree inclined stirrups and shear span to depth ratio of 2.2. As shown in Figure 7 and Table 4, shear capacity calculated by using shear model of EN-2, which uses variable strut inclination angle, is relatively in a better agreement with the experimental results than shear capacity calculated by using ACI 318-14.

Generally, the code predictions are conservative compared to experimental tests and numerical results. Figure 7(a) clearly shows that the conservativeness of ACI 318-14 shear capacity prediction is higher in beams with an inclined arrangement of stirrups. In addition to this, the deviation between the two values is higher in the case of beams with a shear span-to-depth ratio of 2.2 compared to beams with a shear span-to-depth ratio of 2.6. Similarly, Figure 7(a) also shows that the variation between shear predictions of EN-2 and test results reduces as stirrup arrangement changes from inclined to conventional vertical. The observed conservativeness of EN-2 is relatively higher in beams with lower shear span-to-depth ratio. As shown in Figure 7(a), the variation between experimental tests and EN-2 shear prediction is lower in beams with a shear span-to-depth ratio of 2.6 than respective beams with a shear span-to-depth ratio of 2.2.

On the other hand, Figure 7(b) clearly shows that as the compressive strength of concrete increase, the variation between code predictions and experimental results generally increase. The rate of increment of deviation is high in the case of EN-2 shear predictions as compared to ACI 318-14 predictions.

One of the reasons for variation between Eurocode 2 and experimental results can be the reason that the truss model with variable angle of compressive struts is based on the lower bound theorem of the theory of plasticity. The lower bound theorem predicts the ultimate capacity that is less than or at most equal to the true value of the collapse load. Moreover, the Variable angle truss approach applied in EN-2 utilizes the effective concrete compressive strength, which is lower than the concrete cylinder strength. Shear resistance with respect to the crushing of compressive struts is determined as the most conservative approach.

6. Conclusions

A total of 21 RC beams were tested in the three-point bending machine to study the effect of inclination of stirrups, shear span to depth ratio, and concrete compressive strength on the shear capacity of RC beams. These beams were modeled numerically to compare the numerical results with experimental tests. In addition to this, the shear capacity was calculated by employing shear provisions of EN-2 and AC318-14 to evaluate their shear provisions. Based on the results obtained by using the above methods, the following conclusions can be drawn:

The inclined arrangement of stirrups has a high effect on the shear capacity of RC beams. But its effectiveness depends on the shear span-to-depth ratio of the beams. The effectiveness of inclined stirrups has reduced as the shear span-to-depth ratio of beams increase. Therefore, the inclined arrangement of stirrups is more effective in the case of short beams than slender beams.

The experimental results showed that shear strength predictions of both ACI 318-14 and EN 2 are generally conservative. However, the conservativeness of the Euro code has reduced with an increase in the shear span-to-depth ratio. And the shear capacity prediction by EN-2 that uses variable strut inclination angle is in better agreement with the experimental results relative to that of the ACI 318-14 prediction.

The results obtained from numerical analysis (FEM) using ABAQUS are in good agreement with experimental results. On this basis, the numerical methods can account for the effect of factors like arrangement of shear reinforcement, shear span-to-depth, and concrete compressive strength on the shear behavior of the beams. It allows replacing experimental tests that are costly and time taking.

Declarations

Author contribution statement

Chalachew B. Hunegnaw & Temesgen Wondimu: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

We would like to acknowledge Bahir Dar Institute of Technology, Department of Civil Engineering for supporting us by allowing to use their laboratory.

References

ACI Committee 318, 2014. Building Code Requirements for Structural Concrete and Commentary (ACI 318-14). American Concrete Institute, Farmington Hills, MI.

CEN (European Committee for Standardization), 2004. Eurocode 2: Design of concrete Structures. Part 1–1: General Rules and Rules for Buildings. NV 1992-1-1: 2004. Comité Européen de Normalization, Brussels, Belgium.

Ethiopian Standards Agency, 2015. Ethiopian Standard 2: Design of Concrete Structures, CEN (European Committee for Standardization), 2004. Eurocode 2: Design of concrete Structures. Part 1–1: General Rules and Rules for Buildings. NV 1992-1-1: 2004. Comité Européen de Normalization, Brussels, Belgium.

ACI Committee 318, 2014. Building Code Requirements for Structural Concrete and Commentary (ACI 318-14). American Concrete Institute, Farmington Hills, MI. CEN (European Committee for Standardization), 2004. Eurocode 2: Design of concrete Structures. Part 1–1: General Rules and Rules for Buildings. NV 1992-1-1: 2004. Comité Européen de Normalization, Brussels, Belgium. Ethiopian Standards Agency, 2015. Ethiopian Standard 2: Design of Concrete Structures Part 1-1: General Rules for Buildings (ES EN 1992-1-1: 2015). Addis Ababa.

Grandic, D., Slucic, F., Grandic, I.S., 2015. Shear resistance of reinforced concrete beams in dependence on concrete strength in compressive struts. Tech. Gaz. 22 (4), 925–934.

Hu, B., Wu, Y.F., 2018. Effect of shear span-to-depth ratio on shear strength components of RC beams. J. Eng. Struct. 168, 770–783.

Moesyadi, M., Naem, M., 2013. Shear reinforcements in the reinforced concrete beams. Am. J. Eng. Res. (AJER) 2 (10), 191–199.

Sayyad, Atteshamuddin, S., Subhash, V., Patankar, 2013. Effect of stirrup orientation on flexural response of RC deep beams. Am. J. Civ. Eng. Architect. 1 (5), 107–111. Available online at. http://pubs.sciencedirect.com/science/article/pii/S20909851130004.

Slovák, M., 2014. Shear failure mechanisms in concrete beams. Proc. Mater. Sci. 3, 1977–1982. Available from: sciencedirect.com.

Smith, M., 2009. ABAQUS/Standard User’s Manual, Version 6.9. Dassault Systèmes Simulia Corp.