Shear capacity of fiber-reinforced concrete beams without transverse reinforcement

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Abstract. This study studied the effect of using fiber on the shear strength of concrete beams without transverse reinforcement. The concrete mixture does not use coarse aggregate and uses stainless steel fiber with a diameter of 0.2 mm and a length of 36 mm. This study explains the effect of concrete quality on shear strength that can be carried by concrete beams with a ratio of 45 / 10.5, 25 / 10.5 and 20 / 10.5. The making of test specimens in this study was a beam of varying lengths of 110 cm, 70 cm and 60 cm while a width of 7 cm, and a height of 12.5 cm. From the test results, the shear stress value is calculated using the formula \( \frac{\sigma}{(b \times d \times \sqrt{f'_c})} > 2 \) in international units, in which the shear capacity value is bigger than the code states. Diagonal tension failure occurs on 110 cm beam and shear tension failure on 70 cm and 60 cm beams.

1. Introduction

Today, many people research to produce concrete mixtures that have high strength. But with the development of the era, the development of concrete technology is also developing so that it has begun to enter the ultra-high performance-concrete generation. Reactive Powder Concrete (also known as RPC) is a concrete that has very high strength and is composed of cement, silica fume, and quartz powder [1].

One way to improve the quality of concrete as a construction material is to add fiber. The purpose of adding fiber is to increase the tensile strength of concrete. Fiber can also improve the concrete shear strength and can be used in planning in the design of reinforced concrete structures [2]. Fiber concrete is a composite material consisting of plain concrete and other materials in the form of fiber. Based on the material, fiber can be divided into four groups, namely steel fibers, glass fibers, artificial fibers, and natural fibers, the amount of fiber added to the concrete mix depending on the type of fiber used and the results to be achieved [3].

Adding fiber into the mixture will reduce workability quickly in line with the increase in fiber concentration and fiber aspect ratio [4]. So to get optimal results there are two things that must be considered carefully. The first thing is fiber aspect ratio, which is the ratio between fiber length (l) and fiber diameter (d). The second thing is fiber volume fraction (Vf), which is the percentage of fiber volume added to each unit of concrete volume [5].
In the ASCE Committee 426 report, the shear strength of concrete with or without reinforcement is the same, which is the value of the shear force that causes tilting cracks. In this case the shear reinforcement is considered to only withstand the excess shear force that can be held by the concrete without reinforcement. Crack in beams as shown in Figure 1 and cross section of a beam shown in Figure 2.

![Cracks in beams](image1)

**Figure 1.** Cracks in beams

![Cross section of a beam](image2)

**Figure 2.** Cross section of a beam

We find that when comparing the relative strength of each beam ($ru = Mu / Mfl$), the transition point is $a / d = 2.5 - 3$ where the beam is critical to shear (the lowest bending moment in failure). $Mu$ are the ultimate moment due to the shear force and $Mfl$ is the ultimate bending moment. In this study examined the shear strength of concrete beams with ratios of $a / d = 4.2857$, $2.3809$, and $1.9047$ without transverse reinforcement where $a$ is a shear span whereas $d$ is the distance of the fiber pressed into the center of the reinforcing steel or the effective height of the beam with shape square cross section which can be seen in Figure 3. For $a / d$ ratio $< 2.5$ it is known that it will be more resistant to shear forces that occur due to curved action (arch action). However, if the $a / d$ ratio $> 2.5 - 3$ then the failure occurs simultaneously with the shear crack that appears [6].

![a/d ratio model](image3)

**Figure 3.** a/d ratio model (Source: Kani, 1967 [6])

Kani found out at the same time that the beam width did not have an important effect on shear strength [6]. He also concluded that shear stress decreases with increasing beam depth as seen in Figure 4.
This study will compare the value of the shear force of the concrete beam with the ratio of $a/d$ is different. This is done to evaluate the pattern of changes in shear force that occur in concrete and incorporate the results of the research obtained into the Derivation of Design Equation graph as shown in Figure 5.

The equation used to calculate the shear strength of concrete is:

$$V_c = \frac{1}{6} \sqrt{f'_c \cdot bw \cdot d}$$

(1)

Where $V_c$ is the shear capacity of normal concrete, then $f'_c$ is the compression stress of the concrete, $bw$ and $d$ are stated previously in Figure 2.

2. Basic Theory

2.1. Concrete

Concrete is a mixture of portland cement, fine aggregate, coarse aggregate and water, with or without additional ingredients that form a solid period (SNI 03-2847-2002, Article 3.12). The main property of concrete is that it has a very high compressive load capacity, but not strong enough to withstand tensile stress. Because concrete is a composite, the quality of concrete is very dependent on the quality of each forming material.
2.2. Fiber-Reinforced Concrete
Fiber-reinforced concrete is a mixture of concrete added fiber into it evenly, both in the form of long fibers and short fibers. The basic idea of adding fiber is to reinforce concrete with steel fibers that are spread evenly into a concrete mixture with a random orientation. So that concrete does not experience cracks that are too early due to loading or heat hydration [7]. The main purpose of adding fiber to the concrete is to increase the tensile strength of the concrete. It should be noted that giving fiber does not add much to the compressive strength of the concrete, but only adds to the ductility of the concrete.

Adding fiber to the concrete mix can provide an advantage in improving some concrete properties [8], i.e:
- Ductility (ductility), which is related to the ability of a material to absorb energy (energy absorption),
- Resistance to shock loads (impact resistance),
- The ability to withstand tensile and bending moments,
- Resilience to meltdown (fatigue life),
- Resistance to the effect of shrinkage,
- Resistance to abrasion, fragmentation and spalling.

2.3. Reactive Powder Concrete
Reactive Powder Concrete (RPC) is a concrete that has very high strength and is composed of cement, silica fume, and quartz power [1]. The main principle in developing RPC according to Richard P. & Cheyrezy M., 1995 [9], is:
- Use of pozzolanic material in the form of silica fume.
- Increasing ductility by adding steel fibers to the concrete mix.
- Giving pressure to increase stir density.
- Perform treatment by heating method (steam curing) to achieve high strength.
- Use of superplasticizer from a type of polymer to improve performance.
- Increase homogeneity by removing coarse aggregates.
- Increase the density of the matrix by optimizing the aggregate grain size.

2.4. Shear Strength of Concrete
Beams are structural elements that support the external load and the weight itself, which results in a bending moment (M) and a shear force (V), as shown in Figure 6.
In the design of reinforced concrete structures, bending is always the first consideration to determine the moment of conditional resistance that can be used to ensure that a collapse can give a warning to the occupants. At the same time, the beam also withstands shear forces due to bending. The characteristic of a failure due to shear force on a reinforced concrete structural element is brittle, not ductile, and its collapse occurs suddenly without warning. This is because the strength of the reinforced concrete structure shear is mainly dependent on tensile strength and tension strength of concrete. Because the tensile strength of concrete is smaller than its compressive strength, the design of shear is very important in concrete structures. For reinforced concrete structural components, if the shear force that works is so large that it is beyond the ability of the concrete to hold it, additional reinforcement is needed to hold the shear.

In reinforced concrete beams stretching the elongated direction, steel reinforcements completely withstand the tensile force arising from bending. Meanwhile, if the working load continues to increase, tensile and shear stresses will also increase along with the load. While the steel reinforcement that is intended to withstand the pull in the beam is not located at the place where the diagonal tensile stress occurs. For this reason, stirrup reinforcement is needed to hold the diagonal tension in places needed.

Thus shear reinforcement has four functions [10] as follows:

- Bear a part of the planned external force (Vu),
- Prevents diagonal crack propagation so that it is not continuous to the tension section of concrete,
- Holding and tying the longitudinal reinforcement to its position so that the longitudinal reinforcement has a good capacity to carry flexure,
- Provide a kind of bond to the concrete area that is depressed if the stirrup is a closed stirrup.

The shear strength of the beam is influenced by the effective height factor (size effect). One of the researchers who conducted a study of this size effect was Kani. Kani conducted research at the University of Toronto, comparing four blocks without shear reinforcement with heights of 6, 12, 24, and 48 inch (153, 305, 610, and 1220 mm). The beam has concrete quality (f'c) = 3800 (26.2 MPa), flexural reinforcement ratio $\rho = 2.8\%$, and the ratio of $a / d$ beams vary from 1 to 10.

We find that when comparing the relative strength of each beam, $\text{ru} = \text{Mu} / \text{MfI}$ (where Mu is the moment that causes the shear force and MfI is the bending moment), that the transition point is $a / d = 2.5 - 3$ where the beam is critical to shear (bending moment lowest when a failure occurs. For the ratio below this limit, the beam will be able to withstand greater shear force due to arch action. However, if
the a / d ratio is above the critical point, then concrete failure occurs along with the sliding crack that occurs.

Mu is the ultimate moment due to the shear force and Mfl is the ultimate bending moment. Then Kani made a graph based on the results of his research and called "valley of diagonal failure". The relationship between ru (relative strength) and the a / d ratio can be seen in Figure 7. Changes in the relative strength of the beam are clearly visible. Along with the effective increase in beam height, its strength will decrease.

![Figure 7. Relationship between the relative strength of beams with a/d ratio (Source: Kani, 1967 [6])](image)

2.5. Types of Failure

There are several types of failures that can occur on a beam without stirrup reinforcement, namely:

1) Diagonal Failure: With increasing shear force the crack will widen and propagate until it penetrates the upper side of the beam until the collapse occurs. The combination of bending and shear forces is a basic cause of diagonal failure [11]. There are several types of diagonal failure that are often encountered, namely diagonal tension failure, shear tension failure, and shear compression failure:

- Diagonal tension failure (Figure 8) occurs in beams with a / d ratios between 2.5 - 6. The crack that occurs spreads through the beam until it reaches the pressure area. When the beam experiences a critical point, the beam will fail due to the failure of the depressed concrete. This crack often occurs without warning and suddenly [11].

![Figure 8. Diagonal tension failure (Source: Ziarra, 1993 [11]).](image)

- Shear tension failure is almost similar to the diagonal tension failure, but occurs generally in beams that are relatively short. Sliding cracks appear to spread on the beam but have not caused collapse on the beam. Further cracks occur around the longitudinal reinforcement of the last flexural crack and can cause loss of bond between longitudinal and concrete reinforcement (Figure 9). When the beam reaches a critical point, the beam will collapse splitting the concrete [11].
Figure 9. Shear tension failure (Source: Ziarra, 1993 [11])

- Shear Compression Failure spreads through the beam causing collapse when it reaches the pressure zone without any signs of a second crack as in the shear tension failure. This failure is called the shear compression failure (Figure 10). This type of failure occurs on relatively short beams. The ultimate load when a failure occurs can exceed the diagonal crack caused by arch action.

Figure 10. Shear compression failure
(Source: Ziarra, 1993 [11])

2) Flexural Failure: Flexural cracks occur due to moments and on long beams. Because of this, cracks get bigger at the point where the maximum moment value. Cracks are increasingly spread when the shear force on the concrete reaches the maximum tensile stress. Cracks that occur almost perpendicular and cause failure of the beam can be seen in Fig. 11 due to the two cases below [11]:
- Under-reinforced beams: occur when flexural reinforcement has melted causing failure of the concrete press area.
- Over-reinforced beams: occur when the concrete compressive area fails first before the flexural reinforcement melts and results in the concrete failure itself.

Figure 11. Flexural failure (Source: Ziarra, 1993 [11])

2.6. Derivation of Design Equation
In ACI-ASCE 326 a comparison graph has been made between with the parameter \( \rho V d / M' \sqrt{f_c} \) composed of 194 blocks of sample. In the graph there is also a line with the equation.

\[
\frac{V}{bd'\sqrt{f_c}} = 1.9 + (2500) \frac{\rho V d}{M'\sqrt{f_c}}
\]  

(2)

Formula (2) calculates the compressive stress in psi. The graph can be seen in Figure 12.
3. Testing Model
Analysis of flexural reinforcement is calculated by planned \( f'c \) 90 MPa, the beam section used can be seen in Figure 13.

For modeling beam specimens, it can be seen in Figure 14 below:

Test object size:
- Cylinder : \( \varnothing \) 10 cm x 20 cm (for strength test only)
- Beams : with a ratio 45/10,5, 25/10,5 and 20/10,5 Number of specimens: 2 cylinders 2 beams

The cement water factor used was 0.18 / 0.2 / 0.22 times the cement period
4. Results and Study

Based on the results of the research and calculations performed, it can be made a recapitulation of the analysis of the shear strength of the beam and how the effect of the increase in the quality of concrete on the shear strength of the beam as seen in Table 1 for fiberless reinforced concrete and Table 2 for fiber-reinforced concrete.

**Table 1. Recapitulation of shear strength analysis on non-fiber beam test objects**

| No. | Beam Length (m) | f'c (N/mm²) | P (kN)   | Vc (kN)  | Vu (kN)  | Mn (kNm) | Mu (kNm) | Failure |
|-----|----------------|-------------|----------|----------|----------|----------|----------|---------|
| 1   | 1.1            | 70.4        | 38.575   | 102.783  | 193.925  | 176.752  | 87.054   | Shear   |
| 2   | 0.7            | 71.08       | 59.405   | 103.278  | 297.655  | 177.339  | 74.348   | Shear   |
| 3   | 0.6            | 71.855      | 76.66    | 10.384   | 383.825  | 177.996  | 76.723   | Shear   |

**Table 2. Strong analyze recapitulation slide on fiber-reinforced beam test objects**

| No. | Beam Length (m) | f'c (N/mm²) | P (kN)   | Vc (kN)  | Vu (kN)  | Mn (kNm) | Mu (kNm) | Failure |
|-----|----------------|-------------|----------|----------|----------|----------|----------|---------|
| 1   | 1.1            | 92.485      | 48.77    | 117.807  | 24.49    | 19.417   | 109.992  | Shear   |
| 2   | 1.1            | 69.1        | 39.79    | 10.183   | 20       | 175.597  | 89.787   | Shear   |
| 3   | 1.1            | 67.945      | 39.245   | 109.752  | 197.275  | 174.533  | 88.561   | Shear   |
| 4   | 0.7            | 90.865      | 69.71    | 116.771  | 34.918   | 190.583  | 87.229   | Shear   |
| 5   | 0.7            | 85.72       | 59.815   | 113.417  | 299.705  | 187.728  | 74.861   | Shear   |
| 6   | 0.7            | 76.98       | 46.58    | 107.479  | 23.353   | 182.001  | 58.317   | Shear   |
| 7   | 0.6            | 83.605      | 93.645   | 112.009  | 46.875   | 186.542  | 93.708   | Shear   |
| 8   | 0.6            | 79.64       | 68.305   | 109.321  | 34.205   | 183.877  | 68.368   | Shear   |
| 9   | 0.6            | 63.535      | 43.88    | 97.643   | 219.925  | 170.116  | 43.943   | Shear   |

Based on the data and test results obtained, calculate the values and then plotted into the derivation of design equation graph which can be seen in Figure 15 below.

**Figure 15. Derivation of design equation graph**
From the results of the calculation, the shear strength graph against the $a/d$ ratio based on changes in concrete quality can be seen in Figure 16.

![Graph of shear strength against a/d ratio](image1)

**Figure 16.** Graph of shear strength against a/d ratio

From Figure 16, we take the data which compression stress is at maximum from each type of the beams, then with comparing the formula (1) and (2) that has been calculated and plotted the values given in Figure 17.

![Graph of shear stress (vu) against a/d ratio](image2)

**Figure 17.** Graph of shear stress (vu) against a/d ratio
From the collected data, we can analyze these results as follows:

- Based on the graph of the shear strength of the a/d ratio, it can be seen that the pattern of changes in vu value due to changes in d resembles the results of research conducted by Kani. In addition, it can also be concluded that the smaller the a/d ratio will be more resistant to the shear force that occurs.

- Based on the Derivation of Design Equation graph, it can be seen that the point obtained from the calculation is above the minimum limit of > 2 and the greater the value of a/d the quality improvement does not have a large effect on the shear stress value.

- Concrete does not have flexible cracks and only shear cracks, can be seen from the calculation results where Mn < Mu. Shear failure in the design beam a/d = 45/10.5 is a type of diagonal tension failure while in the design beam a/d = 25/10.5 and 20/10.5 is a type of shear tension failure.

- Comparing Figure 15 and 16, there is a significant increase in shear capacity of concrete. This is because the formula that is being used in the code does resemble a regression from the data that they gathered. Based on the experiment, the shear capacity does increase significantly at one point of the shear stress beam.

5. Conclusion

Based on the results of laboratory testing and data analysis, conclusions are obtained, among others:

- Smaller the a/d ratio will be more resistant to the shear force that occurs.
- The greater the value of a/d, the quality improvement does not have a large effect on the shear stress value.
- Comparing the experiment and from the code, there is a significant increase in shear capacity of concrete.

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**Nomenclatures**

- \( b,d \) dimensions of beam \( \text{mm} \)
- \( b_w \) effective width of beam section \( \text{mm} \)
- \( d \) effective height of beam section compression strength of concrete \( \text{N/mm}^2 \)
- \( M \) ultimate bending force \( \text{N/mm} \)
- \( V_c \) shear strength concrete \( \text{N} \)
- \( V_u \) ultimate shear force \( \text{N} \)
- \( \rho \) ratio of reinforcement