ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

EXPERIMENTAL INVESTIGATION OF CONSTRUCTION JOINT IN RC BEAMS

A Thesis in Structural Engineering

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A Thesis

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Abstract

Construction joints are stopping places in the process of placing concrete and they are required because in many structures it is impractical to place concrete in one continuous operation. The region which separates the two dissimilar concretes is called interface. The concept of concrete to concrete interface load transfer plays an important role in assuming the monolithic behavior of the resulting composite reinforced concrete members.

Many researches have been done over the years to understand the interface shear transfer of precast elements and joints. However, most of the researches conducted to study interface shear strength are on pre-cracked or monolithic push off samples and not on construction joints. But the behavior of construction joints cannot be modeled by samples with or without cracks. So a study in samples with construction joint could be valuable contribution to an already existing vast knowledge on interface shear transfer.

The results of the experimental tests indicated that the presence of a construction joint reduces the interface shear strength. Shear strength reduction up to 35% is noted. The test results also show that the shear strength of both samples with and without construction joints increased as the area of steel crossing the shear plane is increased. The shear strength of the monolithic samples increased from 2.91MPa to 2.97MPa to 3.06MPa and the shear strength of samples with construction joint generally increase from 2.36MPa to 2.65MPa. We can also see from the test results that surface treatment could have a major effect in the interface shear strength. The test result shows that the shear strength for a construction joint with a smooth surface treatment is reduced from 2.91MPa to 1.91MPa (which is a 35% reduction). This reduction is mainly due to the reduction in the aggregate interlock forces because of the relatively smooth interface between the two forces of the shear plane.

The experimental results were compared against shear interface models proposed by different researchers and building codes. From this comparison, we can see that the results by the building codes and most researchers are very conservative for both samples with and without construction joint.

Acknowledgment

I would like to express my deepest gratitude to my advisor and mentor Dr. Ing. Adil Zekaria for his continuous encouragement, material supply, valuable and continuous guidance through the course of this study.

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Table of Contents

List of Tables

List of Figures

SECTION 1. INTRODUCTION

1.1. General Background of the Study

1.1.1. Joints in Concrete Structures

The word 'joint' is used in building parlance to cover elements which have to perform quite different functions, e.g. beam-column joints and isolation joints. In the former, the joint has to provide continuity of structural action between the members meeting at the joint. In the latter, the joint has to ensure separation between the adjacent members to allow one member to move independently of the other.

Any joint, as in physical break or gap between members, in a concrete structure or building is a potential **weak link** which may lead to **serviceability** problems, lack of **durability** or **structural failure**. Yet seldom, if ever, is a building constructed without them. In many situations, they are necessary requirement (e.g. to accommodate anticipated differential movement between members) and are sometimes regarded as a necessary evil. Frequently, problems arise because they are given insufficient attention by designers both in terms of their location and detail design.

1.1.2. Why Joints Are Needed

Joints are necessary in concrete structures for a variety of reasons. Not all concrete in a given structure can be placed continuously, so there are construction joints that allow for work to be resumed after a period of time. Since concrete undergoes volume changes, principally related to shrinkage and temperature changes, it can be desirable to provide joints and thus relieve tensile or compressive stresses that would be induced in the structure. Alternatively, the effect of volume changes can be considered just as other load effects are considered in building design. Hence the four basic reasons for requiring joints are because:

- The member or structure cannot be constructed as a monolithic unit in one placement of concrete;
- The member has to be of limited size so it can be handled by cranes, etc;

- The structure or member on one side of the joint needs to be able to move relative to that on the other;
- The design assumptions for the structure or building need the joint at that point so the analysis is simplified.

1.1.3. Joint Requirements

Designers and specifiers of joints should have a clear understanding of the specific requirements for any joint on a specific project. These will range from weather tightness to ease of maintenance and repair. However, there are a few aspects which warrant discussion before looking at the specific joint types:

- Build-ability and minimum size
- Maintenance and repair
- Sealants

1.1.4. Construction Joints

A construction joint is defined by ACI (ACI 224, 1995) as ‘the surface where two successive placements of concrete meet, across which it may be desirable to achieve bond and through which reinforcement may be continuous. Generally, because continuity of structural action will be required across the joint, bond will be desirable and the reinforcement will be continuous.

1.2. Statement of problem

Construction joints are normally required in construction works because there is limited supply of fresh concrete in construction sites in a single day and the size of concrete pour may be too large to be placed in one go. Especially in Ethiopia where the concrete production process is not that developed, around **24 m^3 per day**, this problem becomes very significant. Thus, careful consideration should be given in selecting the location and orientation of the construction joint. Construction joints should be located where they will least affect the structural integrity of the element under consideration, and be compatible with the building’s appearance. Placement of joints varies, depending on the type of element under construction and construction capacity (in this paper beams will be addressed).

In the Ethiopian practice, construction joints for beams and slabs are usually located at about **one-third** of the span length. The choice of this location is based on the consideration of low bending moment anticipated at this point. However, according to ACI (ACI 224, 1995) desirable location for joints placed perpendicular to the main reinforcement are at points of minimum shear or points of contra-flexure. And also in Ethiopian practice, the construction joints are usually made at 45 degree (possibly for better bondage) but most international codes specify that the joint should be vertical or perpendicular to the main reinforcement.

Many researches have been done over the years to understand the interface shear transfer of precast elements and joints. However, most of the researches conducted to study interface shear strength are on pre-cracked or monolithic push off samples. If you see from Mast (Mast, 1968) to Mattock (Mattock, et al., 1976) to Walraven (Walraven, 1980) and Randal (Randal, 2013) all have studied samples with or without cracks and not on construction joints. As the nature of construction joint can be either of the two, a study on shear transfer mechanism of construction joints can provide an additional dimension towards understanding of the mechanism.

In this paper, it was planned to investigate the effect of construction joints so as to properly determine the location and orientation of the construction joints.

1.3. Research objectives

The main objective of the research is to study the effect of construction joint on the interface shear strength of reinforced concrete beams.

1.4. Methodology and Scope

1.4.1. Methodology

The experimental design method was employed to accomplish this study. The overall flow of the study has the following outline:

1. **Literature Review:-** Thorough review of relevant literature, publications, books, manuals, articles, and codes have been undertaken to understand previous works and to look for supportive ideas.
2. **Material Preparation:-**All the necessary materials have been selected and prepared. That is, aggregates and cement will be made ready in such a way that they are suitable for mixing.
3. **Sample Preparation: -** All in all 10+3 push off samples have been prepared. These samples have been prepared for different degrees of confinement bars with and without construction joints in the shear plane. Two types of confinement bars (external and internal) were used to understand the effect of dowel action in the interface shear strength of reinforced concrete beam. One sample was also prepared with smoothened surface to see how much the surface treatment could affect the interface shear strength.
4. **Testing and Analyzing: -** each sample was tested using universal compression machine. Transducers were used to measure the horizontal and vertical displacements of the sample. Strain gauges were also used to measure the amount of force in the external confinement bars. The effect of the construction joint was quantified by the ultimate shear stress of the samples.
5. **Conclusions and Recommendations: -** Finally conclusions and recommendations have been forwarded. Here the findings were summarized and some areas for further research were recommended.

1.4.2. Scope of the study

This research was conducted to understand the effect of vertical construction joints on the interface shear strength of reinforced concrete beams. The effect of horizontal construction joints is not part of the study. The samples were also tested using load controlled compression machine and the post-peak behavior of the samples is not investigated.

The study was also conducted for limited amount of external confinement and the effect of high degree of confinement is not studied. The tests are also conducted for a limited grade of concrete and steel. The geometrical effect of the push of samples is not part of the study.

1.5. Significance of the research

This research can benefit the construction sector in Ethiopia by providing valuable guidance to determine the proper location and orientation of construction joints-this would be helpful form serviceability, durability and structural point of view.

1.6. Outline of the thesis

The thesis is organized in six sections. The first section has covered the background, statement of the problem, motivations, objective, methodology, and scope of the study and research significance. A comprehensive literature survey on the different aspects of interface shear transfer and push of test is presented in section two. A detailed description of how the materials were prepared is included in section three. In this section, a detailed description of how the push-of samples were prepared is also included. In section four a detailed description of the laboratory set up and testing procedure were presented. Results of the experimental study are presented in section five. Discussions and interpretations of the presented results are also presented in this section. Section six is devoted to conclusions and recommendations.

SECTION 2. INTERFACE SHEAR TRANSFER

2.1. Basic Mechanism of Interface Shear Transfer

Construction joint is formed, whenever a new concrete is cast over an existing concrete (concrete where hardening process has already finished). There are many situations that necessities the casting of new concrete on an existing concrete. Some of these situations are:

- Repair and strengthening of existing reinforced concrete members by means of new concrete sections. For instance, reinforced concrete bridge decks and building slabs are often strengthened by adding a concrete overlay. Reinforced concrete jacketing of columns and beams is also commonly used in strengthening operations.
- Connection between precast elements and cast-in-place concrete topping.
- Construction joints between sections cast in place one after the other (this is because it is impractical to place concrete in one continues operation).
- Load transfer via concrete elements at specific sections (e.g. corbels, bearing shoes, ledger beam bearings…).

The region which separates the two dissimilar concretes is called interface. In these situations, the concept of concrete-to-concrete interface load transfer plays an important role in assuming the monolithic behavior of the resulting composite reinforced concrete members. In these situations we have to consider the transfer of three types of forces:

- Transfer of tension force,
- Transfer of compression force,
- Transfer of shear force,

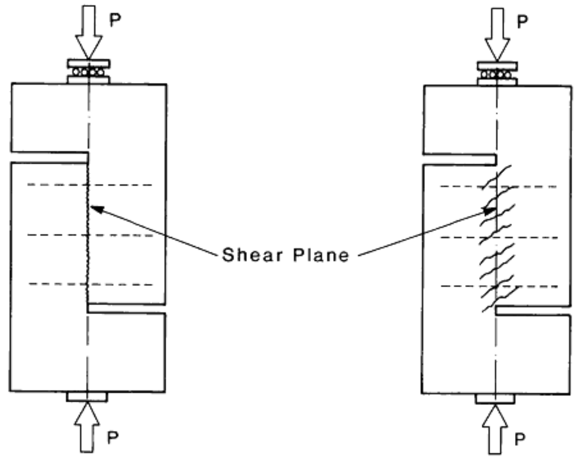
According to Randal (Randal, 2013), while external tensile forces are transferred via reinforcement crossing the interface, compression forces are directly transferred through the concrete. The main task is to ensure the transfer of shear forces along the joint. Over the years many researches have been conducting tests to understand the mechanism of interface shear transfer.

Shear transfer mechanism exhibits two kinds of distinct behaviors, which are: - shear transfer across an initially un-cracked plane and shear transfer across an initially cracked plane. The difference in their behavior is mainly due to the fact that the reinforcement doesn’t come in to play before cracking. Thus, reinforced concrete is closer to isotropic material before cracking and closer to anisotropic after cracking (Walraven, 1980).

An attempt has been made to study concrete shear transfer mechanism along construction joints. However, most researchers concentrate on studying the interface shear strength on pre-cracked or monolithic push off samples. If you see from Mast (Mast, 1968) to Mattock (Mattock, et al., 1976) to Walraven (Walraven, 1980) and Randal (Randal, 2013) all have studied samples with or without cracks and none on construction joints. As the nature of construction joint can be either of the two, a study on shear transfer mechanism of construction joints can provide an additional dimension towards understanding of the mechanism.

1. <u>Shear transfer across an initially un-cracked plane</u>

The shear failure across initially un-cracked plane occurs after numerous cracks are formed at an angle to the shear plane, as shown in Figure 2. 1. The shear load is resisted by a truss-like action formed by the compression force in the struts, which are formed parallel to the cracks and the tension force in the reinforcing bar crossing the shear plane. According to Thomas (Thomas T.c.Hsu , S.T. Mau, and Bin Chen, 1987) failure is commonly due to crushing of concrete in the compression strut.



a). Initially Cracked b). Initially Uncracked

Figure 2. 1: Shear transfer test specimens (Thomas T.c.Hsu , S.T. Mau, and Bin Chen, 1987)

2. Shear transfer across an initially cracked plane

The interface shear transfer mechanism in cracked section is possibly described in terms of five basic mechanisms which are: - mechanical interlock, adhesive bonding, friction, dowel action, and axial restraint. This classification is due to the most general situation of a shear transfer with connectors and possibly also external compression forces acting perpendicular to the shear plane (Randal, 2013).

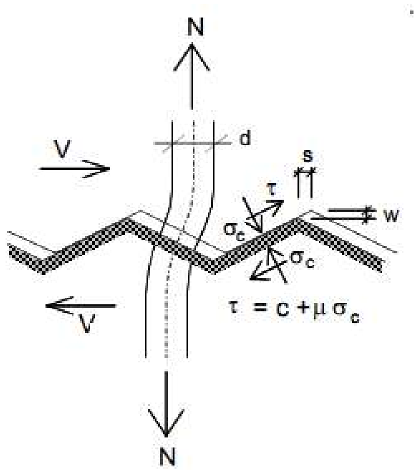
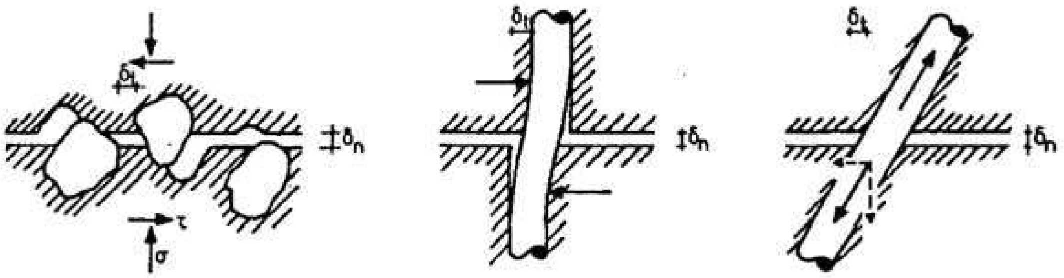


Figure 2. 2: Mechanism of interface shear resistance (Randal, 2013)

a) <u>Mechanical interlock</u>

The mechanism of mechanical interlock prevails due to the fact that when a crack is developed in a concrete mass the surfaces of the crack are usually rough and irregular. This roughness and irregularity exists because in medium strength concrete the coarse aggregate is stronger than the cement and sand matrix, hence the cracks will go through the matrix but around the aggregates. This mechanism is shown in Figure 2. 3. a.



a). Mechanical interlock b). Dowel action c). Axial steel stress

Figure 2. 3: Transfer mechanism in cracked reinforced concrete

When this kind of crack forms along a continuous plane, a parallel displacement in this plane is possible and; therefore, protruding particles from one face of the crack come in to contact with the matrix of the other face. Further movement is, then, restricted by the bearing (interlocking) of the aggregate particles on the crack surface. Provided that there is a reinforcement bar crossing the shear plane, which can prevent large increase in the crack width (see δ_n in Figure 2. 3), a substantial force could be resisted.

b) <u>Adhesive bonding</u>

Adhesive bondage in concrete is due to physical and chemical bonding which is also known as Van der Waals forces. Substantial shear force could be transferred across the interface due to this force. This force is effective only for a relatively very small shear slip (not larger than about 0.05mm); otherwise, its effect will break down (Randal, 2013).

c) <u>Friction</u>

Whenever there is a normal force perpendicular to the shear plane, a friction resistance is developed. In push-off test, the normal force could be applied from the outside and/or due to the clamping force generated by the reinforcement crossing the shear plane as shown in Figure 2. 4 and Figure 2. 2.

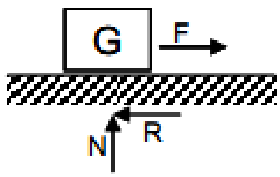


Figure 2. 4: Friction

The mechanism of frictional shear transfer can be described by Figure 2. 2. The interface, as shown in the figure, is crossed by a reinforcing bar of area A_s. This interface is subjected to a shear stress, **V,** causing a shear displacement, **S**. Because of the already developed rough and irregular cracks, as discussed in section 2.1, the relative displacement between the two faces causes some deformation perpendicular to the slip. This local increase of the crack width, **W**, is known as lateral dilatancy. Because of the dilatancy a tension force, $\mathbf{NA_s}$, is developed in the bar crossing the concrete interface. This tensile force develops a clamping force of, $\boldsymbol{\sigma_c A_c}$, around the vicinity of the bar, where $\boldsymbol{\sigma_c=\rho\sigma_s}$. It is as a result of this clamping (compression) force that a shear friction resistance is developed at the interface which is commonly expressed as $\tau_{fr} = \mu\sigma_c$.

d) Dowel action

Dowel action is defined as the capacity of reinforcing bars to transfer forces perpendicular to their axis as shown in Figure 2. 2.b. According to Walraven (Walraven, 1980), there are three different mechanisms of dowel action as shown in Figure 2. 5. These are:

- Load transfer by bending
- Load transfer by pure shear
- Load transfer by kinking

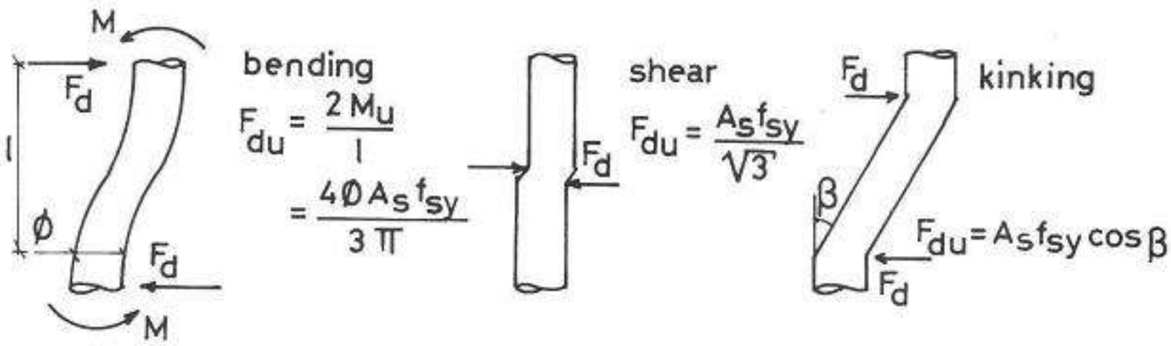


Figure 2. 5: Mechanism of shear transfer over the free length

(Walraven, 1980)

e) Axial restraint

The reinforcing bars usually cross the crack plane at different angles. The component of the steel stress parallel to the crack plane contributes to the shear stress transfer across the crack as depicted in Figure 2. 3.

2.2. Factors affecting interface shear transfer strength

Various studies were made on the factors affecting interface shear strength. The major factors affecting interface shear transfer are:

a) Characteristics of the shear plane
b) Characteristics of roughness of crack face
    - Global roughness
    - Minor roughness
c) Characteristics of concrete
    - Concrete strength
    - Concrete composition
    - Scale of the aggregate
    - Aggregate type
d) Characteristics of reinforcement crossing shear plane(Stirrups)
    - Bar diameter
    - Bar number (spacing)
    - Yield strength f_y of the bar
    - Bar arrangement
    - Inclination of the stirrup to the crack plane
e) Dowel action
f) Direct stress acting parallel to the shear plane
g) Direct stress acting transverse to the shear plane
h) Type of loading
    - Single direction (static)
    - Cyclic reversal of loading (static)
    - Sustained loading

1. **Characteristics of the shear plane**

Mast (Mast, 1968) pointed out the need to consider the presence of crack along the shear plane before shear is applied. Such cracks can occur for a variety of reasons unrelated to shear, such as tension forces caused by restrained shrinkage or temperature deformations. Thus, many researchers tried to investigate the presence of pre-existing crack by intentionally introducing cracks along the shear plane before applying the shear load.

The presence of pre-existing crack generally reduces the shear transfer strength. However, for larger ratio of reinforcement crossing shear plane ($\rho f_y \geq 9.4$MPa), the strength of cracked and un-cracked specimens are approximately the same as shown in Figure 2. 6. Moreover, it was found that the presence of crack would definitely increase the slip at all stages of loading (Hofmeck,J.A.,Ibrahim,I.O. and Mattock,A.H.,, 1969).

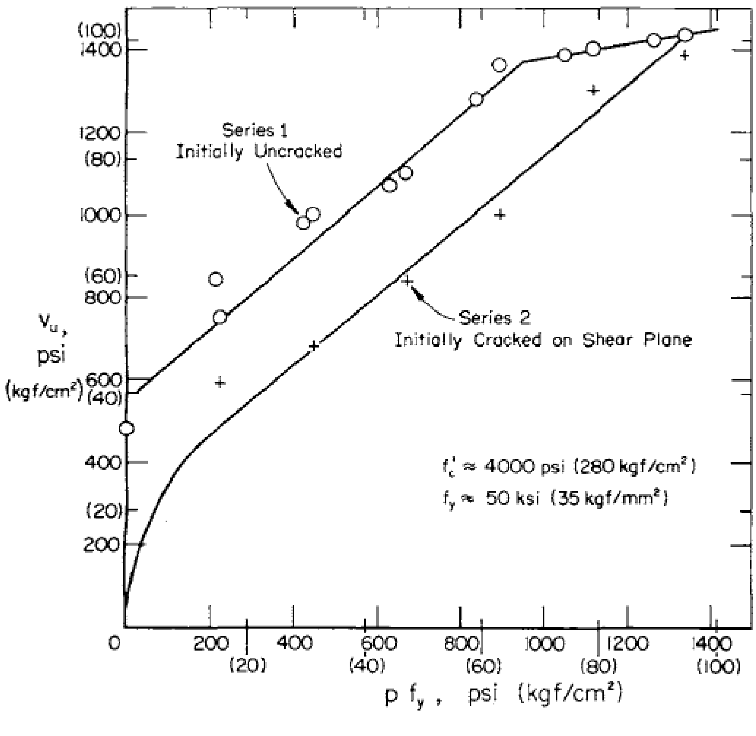
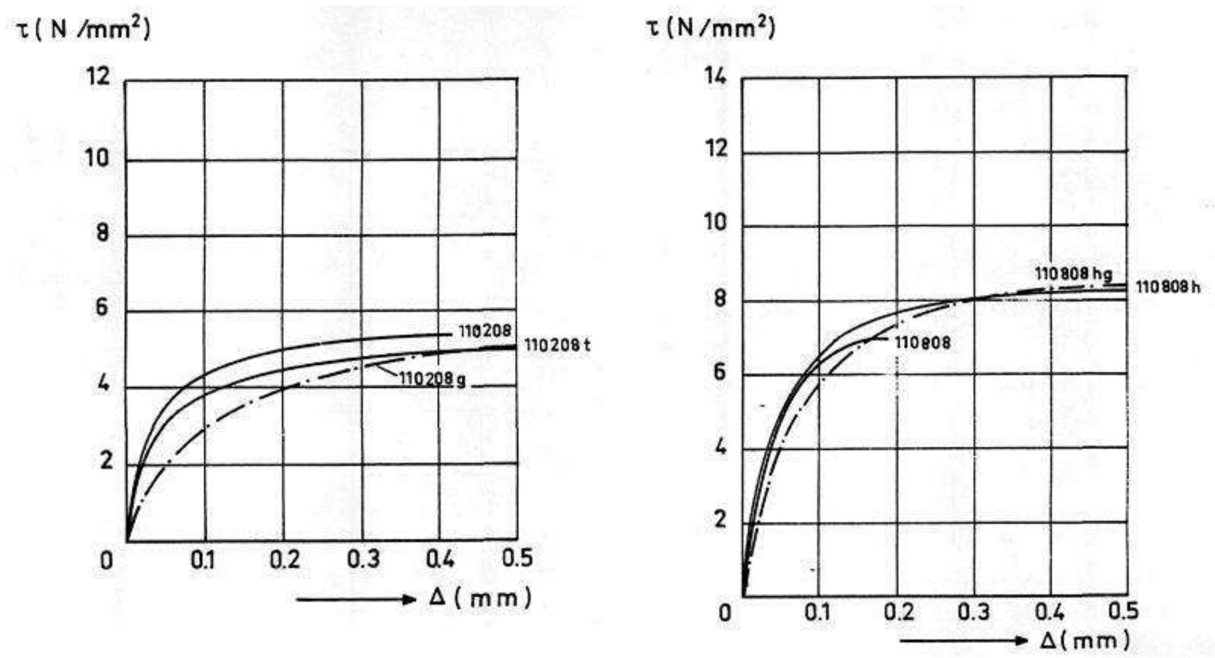


Figure 2. 6: Variation of shear strength with reinforcement parameter ρfy, with and without a crack along the shear plane

(Hofmeck,J.A.,Ibrahim,I.O. and Mattock,A.H.,, 1969)

2. **<u>Initial crack width</u>**

The effect of initial crack width is presented in Figure 2. 7. Accordingly, the shear strength decreases as initial crack width increases. It can also be seen that the τ-Δ relation lines of the specimen with the greater initial crack width (broken line in the figure) tend to join the lines of the other specimens indicating that specimens with different initial crack width do not follow the same crack opening path. (Walraven, 1997)



110208: Mix-1, f'_{cc} = 30.7 N/mm^2, 2ϕ8 stirrups, W_o = 0.02mm

110208t: Mix-1, f'_{cc} = 35.9 N/mm^2, 2ϕ8 stirrups, W_o = 0.03mm

110208g: Mix-1, f'_{cc} = 29.4 N/mm^2, 2ϕ8 stirrups, W_o = 0.09mm

110808: Mix-1, f'_{cc} = 30.7 N/mm^2, 8ϕ8 stirrups, W_o = 0.02mm

110808h: Mix-1, f'_{cc} = 29.4 N/mm^2, 8ϕ8 stirrups, W_o = 0.01mm

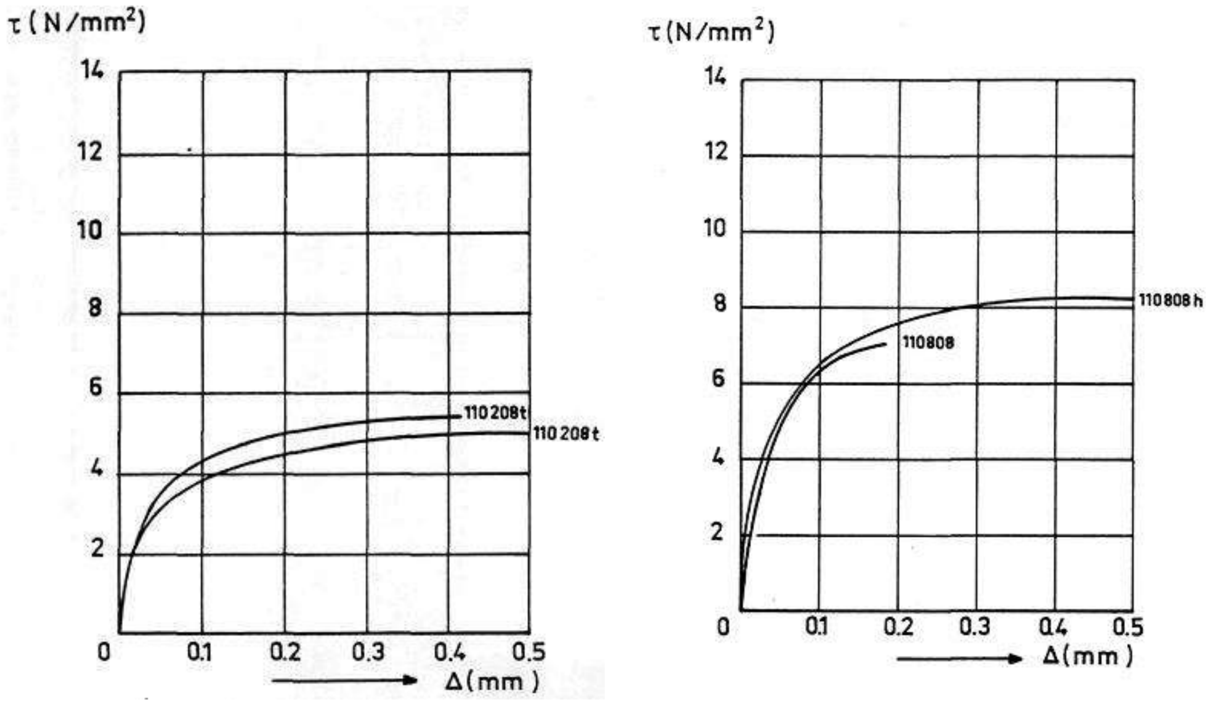
110808hg: Mix-1, f'_{cc} = 29.4 N/mm^2, 8ϕ8 stirrups, W_o = 0.07mm

Figure 2. 7: Influence of initial crack width W_o on the shear strength

(Walraven, 1997)

3. **<u>The influence of the accidental, global, roughness of the cracks</u>**

To investigate the influence of the global structure of a crack Walraven (Walraven, 1997) prepared and tested two comparable samples. The results indicated that the global structure of a crack plane doesn't have a substantial effect on the interface shear strength as shown in Figure 2. 8. This perhaps indicating that concrete is not as heterogeneous as we all think.



110208: Mix-1, f'_{cc} = 30.7 N/mm^2, 2ϕ8 stirrups, W_o = 0.02mm

110208t: Mix-1, f'_{cc} = 35.9 N/mm^2, 2ϕ8 stirrups, W_o = 0.03mm

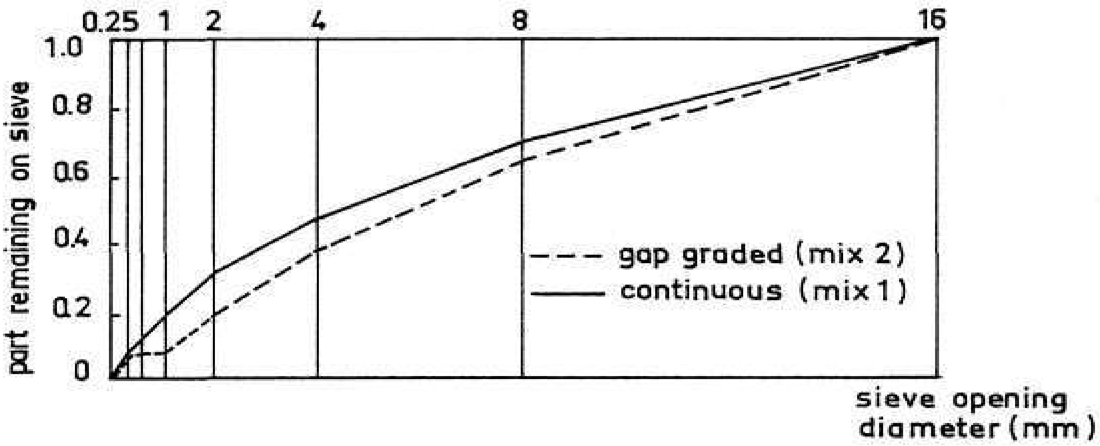
110808: Mix-1, f'_{cc} = 30.7 N/mm^2, 8ϕ8 stirrups, W_o = 0.02mm

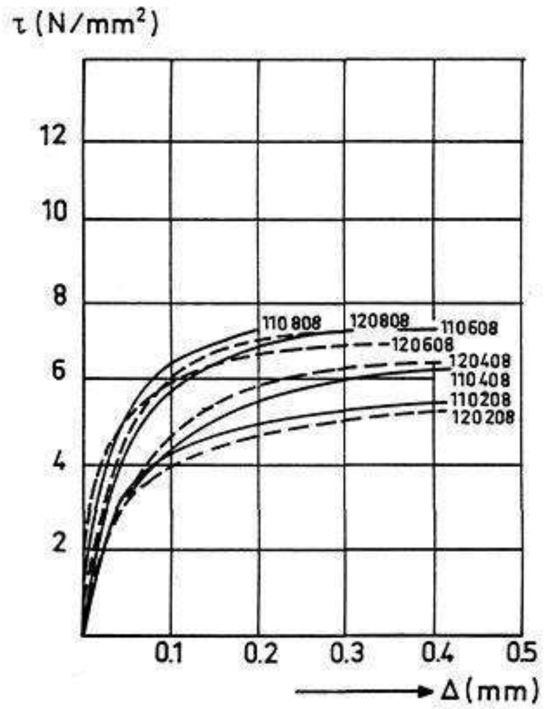
110808h: Mix-1, f'_{cc} = 29.4 N/mm^2, 8ϕ8 stirrups, W_o = 0.01mm

Figure 2. 8: Comparison of the behavior of two similar specimens (Walraven, 1997)

4. **<u>The influence of variations in minor roughness of the crack faces</u>**

To investigate whether the sand fractions of concrete mixtures could play a dominant role in the behavior of reinforced cracks, a gap graded mix was prepared whereby all particles with sizes between 0.25 and 1mm were removed and replaced with quartz powder to obtain a feasible mixture. After comparing mix-1 and mix-2, as can be seen from Figure 2. 9, no significant differences were observed. (Walraven, 1997)





110808: Mix-1, f'_{cc} = 29-30 N/mm^2, 8ϕ8 stirrups

120808: Mix-2, f'_{cc} = 29-30 N/mm^2, 8ϕ8 stirrups

110608: Mix-1, f'_{cc} = 29-30 N/mm^2, 6ϕ8 stirrups

120608: Mix-2, f'_{cc} = 29-30 N/mm^2, 6ϕ8 stirrups

120408: Mix-2, f'_{cc} = 29-30 N/mm^2, 4ϕ8 stirrups

110408: Mix-1, f'_{cc} = 29-30 N/mm^2, 4ϕ8 stirrups

110208: Mix-1, f'_{cc} = 29-30 N/mm^2, 2ϕ8 stirrups

1202808: Mix-2, f'_{cc} = 29-30 N/mm^2, 8ϕ8 stirrups

Figure 2. 9: Comparison of the influence of the elimination of the sand fraction between 0.25-1.00 mm on the shear strength

(Walraven, 1997)

5. Concrete Strength

Generally, the interface shear transfer strength increases with increasing grade of concrete (Hofmeck,J.A.,Ibrahim,I.O. and Mattock,A.H.,, 1969) (Mattock,A,H, and Hawkins,N,M.,, 1972). But there is an upper limit value of ρf_y, below which the shear transfer strength is the same for all grade of concrete as shown in Figure 2. 10. For instance, the relationship developed for 280kgf/cm^2 (28MPa) concrete would hold for any strength of concrete equal to or greater than 28MPa, and above which the shear strength increases at a lesser rate.

6. Aggregate type

The interface shear transfer strength of lightweight concrete (which is being used in precast concrete construction) is less than that of sand and gravel concrete of the same compressive strength (Mattock, et al., 1976).

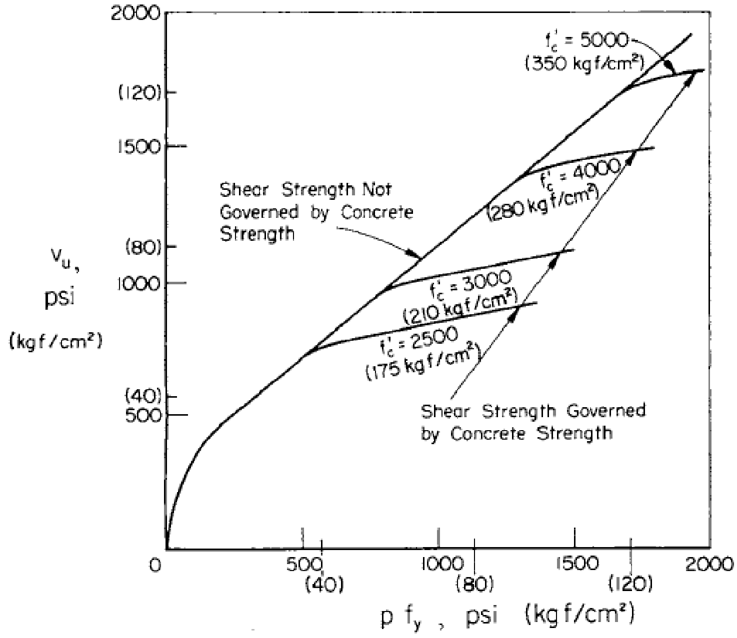


Figure 2. 10: Possible relationship between V_u and ρf_y for initially cracked specimens of various concrete strengths

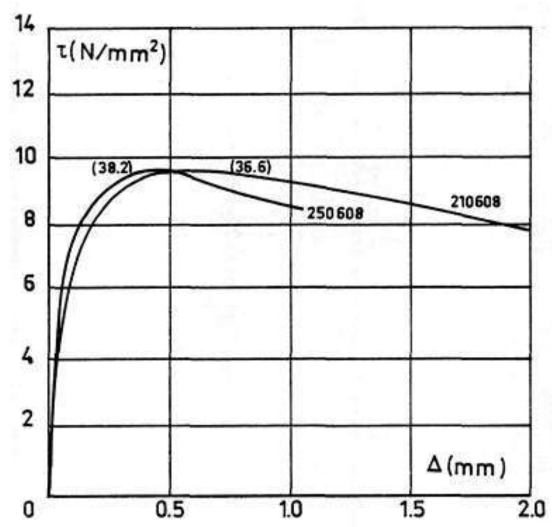
(Hofmeck,J.A.,Ibrahim,I.O. and Mattock,A.H.,, 1969)

7. **<u>The influence of the scale of the aggregate</u>**

   Two samples were tested by Walraven (Walraven, 1997) to investigate the influence of scale of the aggregate (maximum aggregate size). As can be seen from Figure 2. 11, the scale of the aggregate doesn't have a considerable effect on the interface shear strength.

8. **<u>Reinforcement ratio ρ</u>**

   For a constant area of shear plane, the value of **ρ** can be changed by varying either the bar diameter or the bar spacing (number). Mattock (Hofmeck,J.A.,Ibrahim,I.O. and Mattock,A.H.,, 1969) stated that as long as the value of ρf_y is kept constant the bar diameter doesn't have any effect on the interface shear transfer strength. However, Walraven (Walraven, 1980) states that slightly higher shear strength was developed by the specimens containing bars with the smallest diameter, this increase is attributed to the dowel action.



210608:Mix-1, f'_{cc} = 36.6 N/mm^{2}, 6ϕ8stirrups, D_{max}= 16mm

250608:Mix-5, f'_{cc} = 38.2 N/mm^{2}, 6ϕ8stirrups, D_{max}= 32mm

Figure 2. 11: The influence of the scale of the aggregate on the shear strength

(Walraven, 1997)

9. **Yield strength of stirrups (f_y)**

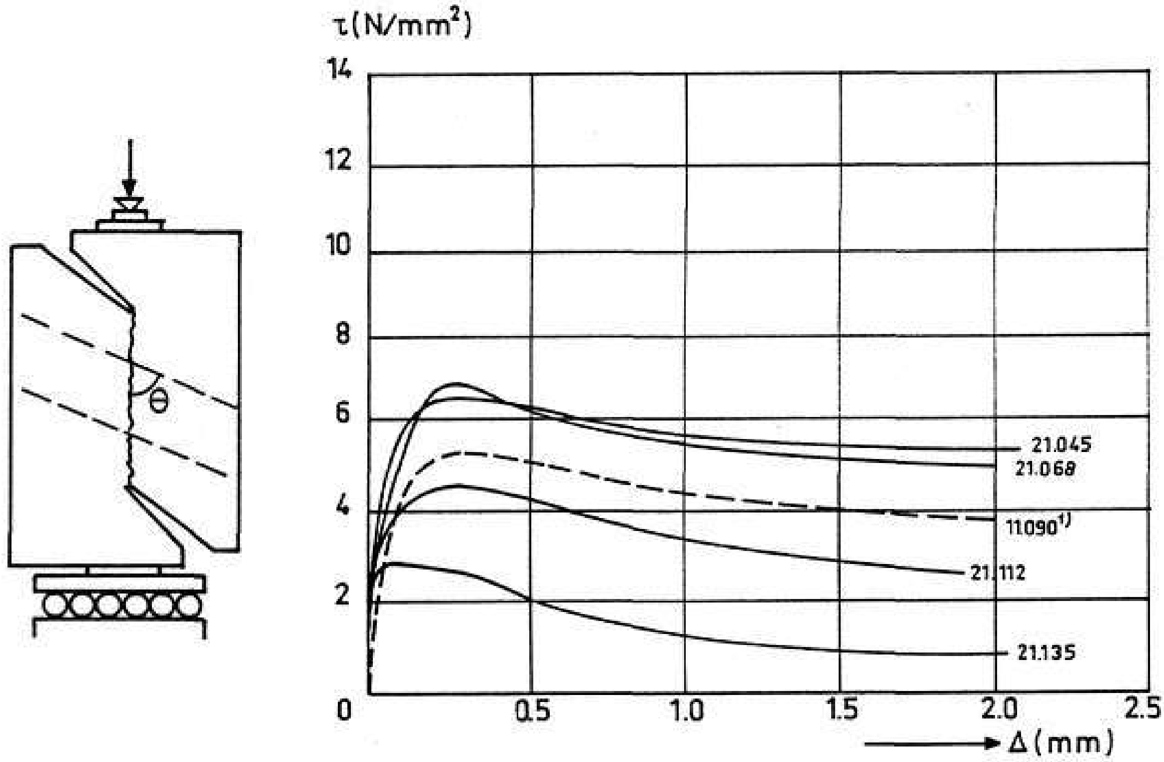
For constant values of ρf_y, the interface strength of the specimens with high strength (low ductility) bars was higher than the specimens with medium strength bars. This was mainly explained by the fact that high strength bars develop a stress greater than their yield point i.e. strain hardening occurred because the yield plateau of high strength bars is considerably shorter (Hofmeck,J.A.,Ibrahim,I.O. and Mattock,A.H.,, 1969).

10. **Arrangement of stirrup**

If shear only is to be transferred across a crack, for a constant value of ρf_y, the interface shear transfer resistance increases provided that the reinforcement is distributed uniformly on the shear plane. This is mainly because, when a crack in a shear plane is subjected to shear only, only that part of the crack crossed by reinforcement is fully effective in resisting slip. However, if both shear and moment are to be transferred across the shear plane, then in order to be fully effective it is better if the reinforcement is placed in the flexural tension zone (Mattock, et al.)

11. The influence of the inclination of the reinforcement to the crack plane

To study the effect of the orientation of the bars crossing the shear plane, Walraven used the set up shown in Figure 2. 12. It can be seen that the shear strength increases with decreasing value of θ.



21.0.45: Mix-1, f'_{cc} = 34.2 N/mm^{2,}, θ=45^o

21.068: Mix-1, f'_{cc} = 34.2 N/mm^{2,}, θ=68^o

11.090*: Mix-1, f'_{cc} = 32.0 N/mm^{2,}, θ=90^o

21.112: Mix-1, f'_{cc} = 34.2 N/mm^{2,}, θ=112^o

21.135: Mix-1, f'_{cc} = 34.2 N/mm^{2,}, θ=135^o

*average of tests 110208,110208t and 110208g

Figure 2. 12: The influence of the inclination of the reinforcement on shear strength (Walraven, 1997)

12. **Dowel Action**

The contribution of dowel action to interface shear transfer across initially un-cracked shear plane is not that significant and can be safely ignored. However, for initially cracked shear plane, there is a considerable contribution to shear transfer strength by dowel action (Hofmeck,J.A.,Ibrahim,I.O. and Mattock,A.H.,, 1969)

13. **Direct stress acting parallel to the shear plane**

For initially un-cracked specimens, a direct tension stress parallel to the shear plane would greatly reduce the interface shear transfer strength. However, for initially cracked specimens, the presence of direct tension force parallel to the shear plane doesn't have significant effect (Mattock,A,H, and Hawkins,N,M.,, 1972).

14. **Direct stress acting transverse to the shear plane**

Externally applied compressive stress acting transverse to the shear plane increases the interface shear transfer strength, and externally applied tension forces reduces the interface shear transfer strength. (Mattock,A,H, and Hawkins,N,M.,, 1972)

15. **Type of loading (static, cyclic and sustained)**

To see the effect of type of loading a number of tests were conducted with static, cyclic and sustained loading. The test results showed that the type of loading doesn't have a significant effect on the interface shear transfer strength (Walraven.J.C.;Frenay. J.;Pruilssers.A.;, 1976).

2.3. Shear Transfer Models

A simple "saw-tooth model" or shear-friction model is usually used by different researchers to simulate the interface shear transfer as depicted on Figure 2. 13. This theory is based on the assumption that the shear strength of concrete-to-concrete interface subjected to shear force is mainly due to friction. The shear loading which results in a relative slippage between two (old & new and/or cracked) concrete layers causes the interface crack width to increase. This causes the steel reinforcement to develop a tensile force, thus compressing the interface. This normal compression force develops a friction force that can transmit the interface shear force.

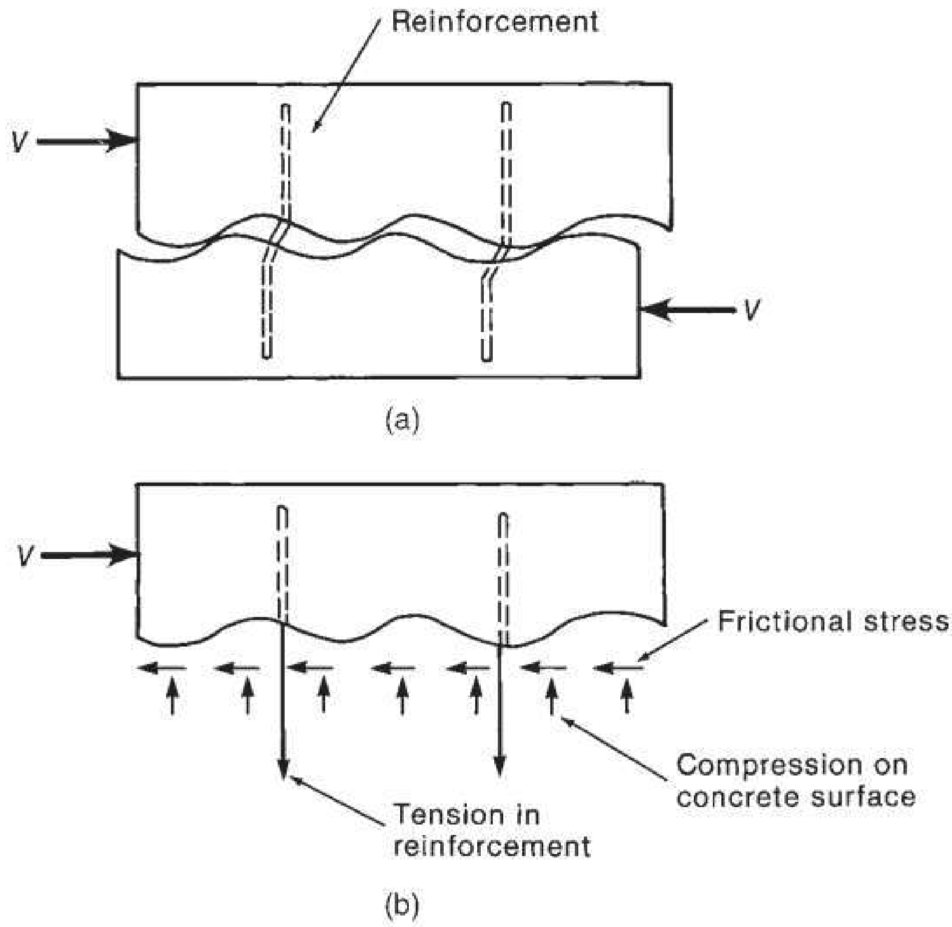


Figure 2. 13: Shear-Friction Model

(Norman.W.H, 1960)

Birkeland and Birkeland (Birkeland P.W, Birkeland H.W, 1966) were the first researchers to propose the shear friction expression. Latter, Mattock and Hawkins (Mattock,A,H, and Hawkins,N,M.,, 1972) proposed an improved design model, known as the “modified shear-friction expression”, which includes a constant term attributed to cohesion. Loov (Loov, 1978) was the first to explicitly include the concrete strength in the interface shear model. Walraven (Walraven, 1980) used a “sphere model” to propose a non-linear function to predict the shear strength of initially cracked interface.

Randal (Randal, 2013) proposed the first design expression that explicitly includes the contribution of:

- Cohesion related with aggregate interlock
- Friction related with the normal stresses to the interface and the longitudinal relative slip between concrete parts
- Dowel action

According to Santos (Santos, 2009), current design codes present design expressions for the assessment of the longitudinal shear strength of concrete-to-concrete interfaces. These expressions are based on the shear-friction theory and the shear strength is evaluated by considering four basic parameters:

1. Compressive strength of the weakest concrete
2. Normal stresses at the interface
3. Shear reinforcement crossing the shear plane
4. Roughness of the substrate surface.

Major milestones in the development of interface shear transfer expressions and provisions of design codes are summarized in

Table 2. **1** and Figure 2. 14.

Table 2. 1: Summary of Interface Shear-Transfer Expressions

a). **Provisions of Design Codes**

I/N	Reference	Design Expression [MPa]	Remark
1	(ACI 318M-05, 2005)	$V_U = \mu \rho_v f_y \leq min \begin{cases} 0.25 f'_c \\ 5.5 \end{cases}$	$\mu \begin{cases} 1.7 \ldots monolithic \\ 1.0 \ldots roughned\ CJ \\ 0.6 \ldots construciotn\ joint \end{cases}$
2	(PCI, 1992)	$V_U = \mu \rho_v f_y$	$\mu = \begin{cases} 1.4 \ldots\ldots \rho_v f_y < 4.14 \\ 1.4 \left(\frac{2.07}{\rho_v f_y} + 0.5 \right) \end{cases}$
3	(Eurocode 2, 2004)	$V_u = c f_{ct} + \mu \rho_v f_y \leq 0.3 f_c$	C=0.35,μ=0.6
4	MC-90	$V_u = 1.49 + 0.9 \rho_v f_y \leq 10.8$	

b). **Shear-friction Milestones**

I/N	Reference	Design Expression [MPa]	Remark
1	(Birkeland P.W, Birkeland H.W, 1966)	$V_u = \mu \rho_v f_y$	$\mu \begin{cases} 1.7 \ldots monolithic \\ 1.4 \ldots roughned\ CJ \\ 0.8 \ldots construciotn\ joint \end{cases}$
2	(Mattock,A,H, and Hawkins,N,M.,, 1972)	$V_u = 2.8 + 0.8 \rho_v f_y \leq 0.3 f'_c$	
3	(Mattock, 1976)	$V_u = 0.467 (f'_c)^{0.545} + 0.8 \rho_v f_y \leq 0.3 f'_c$	
4	(Walraven, 1980)	$V_u = 0.878 (f'_c)^{0.406} (\rho_v f_y)^a \leq 0.3 f'_c$	$a = 0.167 (f'_c)^{0.303}$
5	(Mau, S T and Hsu, T T.C;, 1988)	$V_u = 0.66 ((\rho_v f_y f'_c)^{0.5} \leq 0.3 f'_c$	
6	(Lin, I J and Chen, Y L, 1989)	$V_u = \mu \rho_v f_y \leq 0.3 f'_c$	$\mu = \begin{cases} \sqrt{\frac{1.75 (f'_c)^{0.5}}{\rho_v f_y}} \\ 1.43 (f'_c)^{0.25} \end{cases}$
7	(Loov, R and Patnaik, A;, 1994)	$V_u = 0.573 (f'_c)^{0.55} (\rho_v f_y)^{0.45} \leq 0.3 f'_c$	
8	(Randal, 2013)	$V_u = c f_c^{1/3} + \mu \rho_v k f_y + \alpha \rho \sqrt{f_y f_c}$	C=0,k=0.5,α=1.1
9	(Mattock, 2001)	$V_u = C + 0.8 \rho_v f_y \leq \begin{cases} 0.3 f'_c \\ 16.5 \end{cases}$	If $\frac{\rho_v f_y}{f'_c} \geq \frac{C}{1.45}$ & $C = \begin{cases} 0.1 \\ \frac{5.517}{f'_c} \end{cases}$
		$V_u = 2.25 \rho_v f_y \leq \begin{cases} 0.3 f'_c \\ 16.5 \end{cases}$	

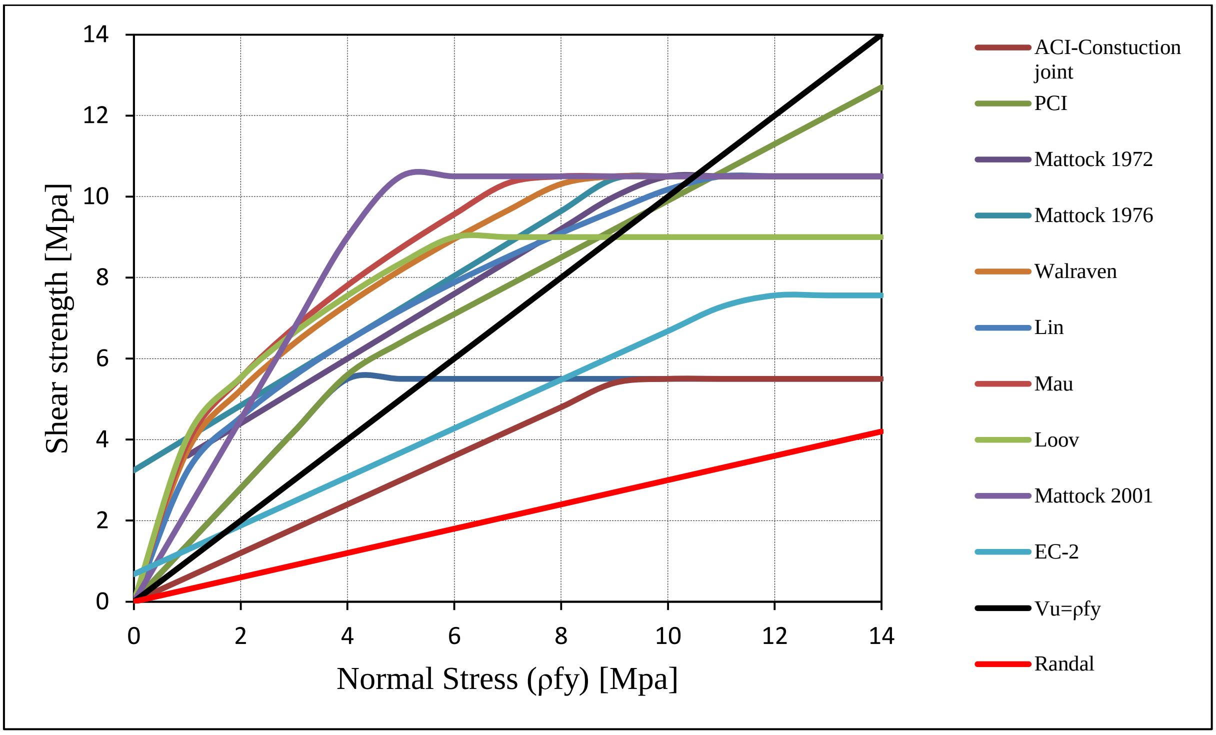


Figure 2. 14: Graphical summary of Interface Shear-Transfer Expressions

As can be seen from the graph the different models used by different researchers and code provisions are scattered over a wide range. Suggesting that there is no general consensus or accepted theory for evaluating the ultimate interface shear capacity of reinforced concrete structures.

SECTION 3. MATERIALS

3.1. Mix design

3.1.1. Cement

For this laboratory work, DERBA OPC of Grade 42 is used. This cement is selected over PPC for its early hardening property. This will reduce the waiting time for placing the second batch of concrete during the lab test.

3.1.1.1. Chemical Composition

3.1.1.2. Physical Properties

The following physical tests have been conducted:

- Normal consistency
- Setting time

3.1.2. Coarse Aggregate

The following physical tests have been conducted:

- Sieve analysis
- Specific gravity and water absorption
- Moisture content
- Unit weight

3.1.3. Fine Aggregate

The following physical properties have been conducted:

- Silt Content
- Sieve Analysis
- Specific Gravity and Absorption
- Moisture Content

3.1.4. Summary of Material Property

Table 3. 1: Summary of Material property

Material Properties	Coarse aggregate	Fine aggregate
Gradation:	it's According to Ethiopian/ASTM C 33-93	it's According to Ethiopian/ASTM C 33-93
Aggregate type	Crushed	Uncrushed
Silt content:		3.23%
Maximum aggregate size:	25mm	
Specific gravity (SSD Basis):	2.85	2.44
Unit weight:	1603mm	
Moisture content:	2.04%	3.1%
Absorption:	2.20%	5.3%

3.1.5. Concrete

The mix design is prepared for 25MPa compressive strength at 28th day.

Table 3. 2: Concrete mix proportion

Constituent materials	**Weight per 1m^3 of concrete (Kg)**	**Remark**
Cement	340	W/C = 0.52
Water	176.8	
Coarse Aggregate	740	
Fine Aggregate	1056	

For the prepared trial mix two tests:

- Slump test and
- Compressive strength test were conducted.

Table 3. 3: Results of Compressive Strength Test

No.	Test Age [days]	Dimensions (cm)			Weight (gm)	Failure Load [KN]	Compressive Strength (MPa)
		L	W	H			
1	**3**	15	15	15	7872	314.1	13.96
2		15	15	15	7825	297.6	13.23
3		15	15	15	7801	317.9	14.13
					Mean	**309.87**	**13.77**
1	**7**	15	15	15	7796	433.2	19.25
2		15	15	15	7895	464.8	20.66
3		15	15	15	7856	432.8	19.23
					Mean	**443.6**	**19.71**
1	**14**	15	15	15	7830	528	23.46
2		15	15	15	7825	531.8	23.64
3		15	15	15	7795	515.9	22.93
					Mean	**525.23**	**23.34**
1	**28**	15	15	15	7805	659.1	29.29
2		15	15	15	7720	649.4	28.86
3		15	15	15	7785		
					Mean	**564.25**	**29.08**

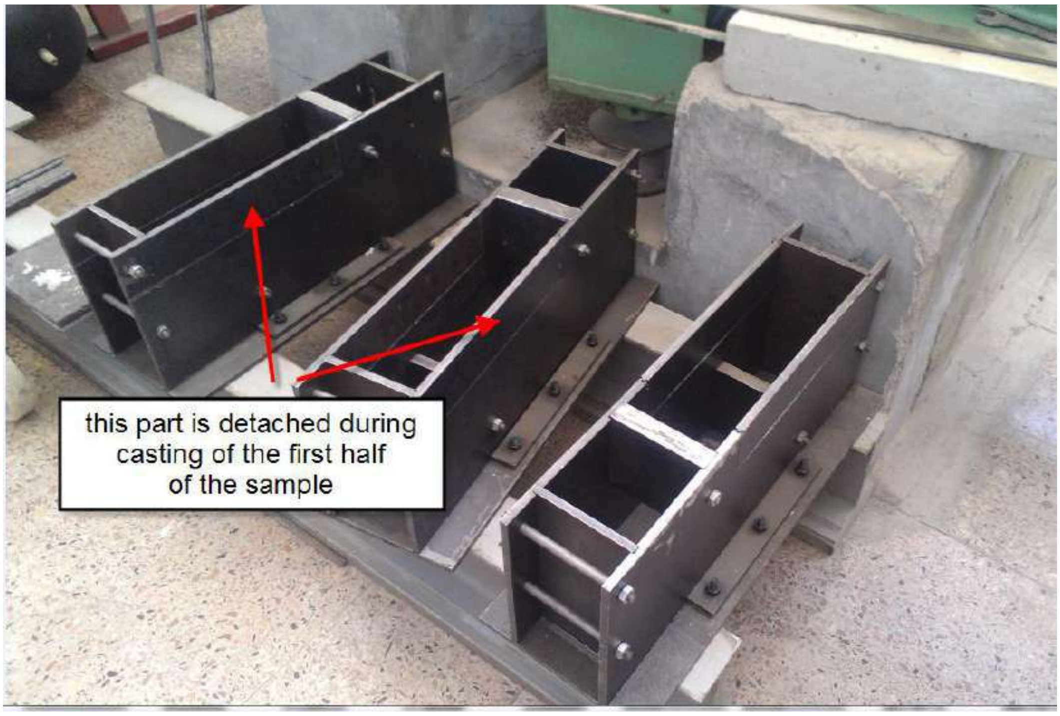


Figure.3. 1: Steel formwork used for preparing push of samples

3.2. Production of push-off specimens

At most care was taken to maintain the consistency of the concrete as it was produced over a period of time. These measures include:

- The coarse aggregate and the fine aggregate were kept in plastic bag to prevent loss of moisture. The effectiveness of this method was checked over the period of time by measuring the moisture content of samples and it was found to be extremely effective in keeping constant moisture content of the constituent materials.
- The production process was kept the same throughout. Each step of the production process (see below) was kept constant. Two major actions were taken to ensure consistency:
    - The process was timed using a stopwatch and kept constant on average

- All subjective process such as the slump test and vibration process were conducted by the same person for consistency.

The production process is summarized below:

Formwork preparation :
- Assembling of Steel formwork (see Figure.3. 1).
- Oiling formwork
- Placing the reinforcement bar with the appropriate concrete cover

Mixing :
- The constituent materials were batched by weight
- Feeding order: Coarse. Agg, Fine Agg, Cement, and water
- The constituent materials were dry mixed for one minute and wet mixed for two minute

Vibration :
- Poker vibrator was used to vibrate the concrete
- Each specimen was cast on the side (see Figure.3. 2)
- Each part (half) of the specimen was vibrated for 5 minute (each)
- Six cube samples were taken from each mix to check the compressive strength

Curing :
- Pond curing was used (each sample was cured for a minimum of 50days)

Figure.3. 2: Casting of Push off Sample

Table 3. 4: Summary of laboratory test results for push-off specimens

Specimen Type	Code	Cube				Remark
		Code	Slump (mm)	Average Weight	Average compressive Strength (Mpa)	
PT-A	PT-A-M-01	PT-A-1	27	7803.33	31.08	
	PT-A-CJ-01	PT-A-2	25	7807.67		
	PT-A-CJ-01*					
PT-B	PT-B-M-01	PT-B-1	28	7738.33	28.87	
	PT-B-CJ-01	PT-B-2	25	7758.33		
PT-C	PT-C-M-01	PT-C-1	30	7749.00	29.03	
	PT-C-CJ-01	PT-C-2	20	8134.67		
PT-D	PT-D-CJ-01	PT-D-1	35	8030.00	34.43	
		PT-D-2	35	7907.50		
PT-A	PT-A-M-02	PT-A-1	20	8050.00	41.83	
	PT-A-CJ-02	PT-A-2	20	8051.67		

* the surface was smoothed with trowel after placing the first part

3.3. Preparation of Push of sample for testing

After curing the push of sample each sample was prepared for testing. Major steps are:

- Marking the location of the side, top, bottom plates, and transducers (see Figure.3. 3). This was done on a water level surface to increase accuracy.

Figure.3. 3: Marking of the sample

- Attaching the side, top and bottom plates to the sample using epoxy (see Figure.3. 4).

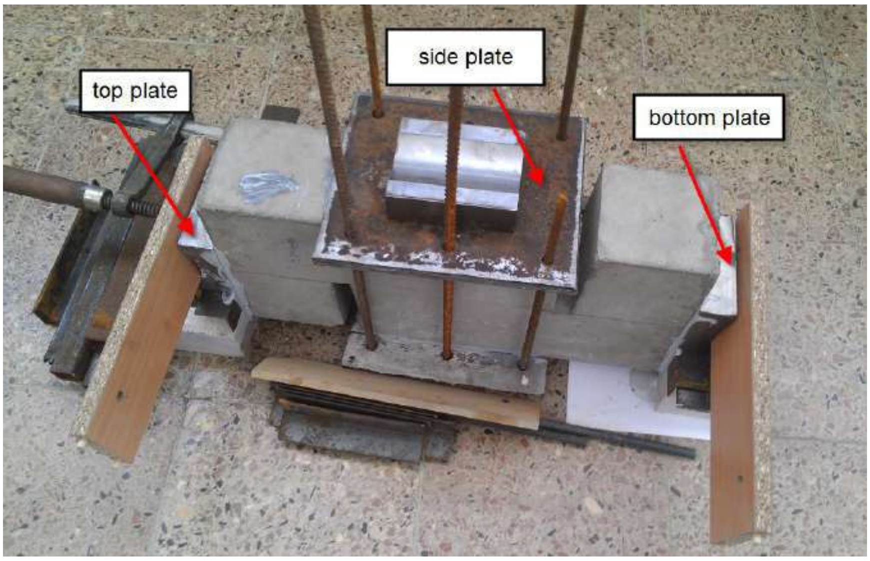


Figure.3. 4: Attaching plates to the sample with epoxy

- Attaching transducers to the samples (see Figure.3. 5).

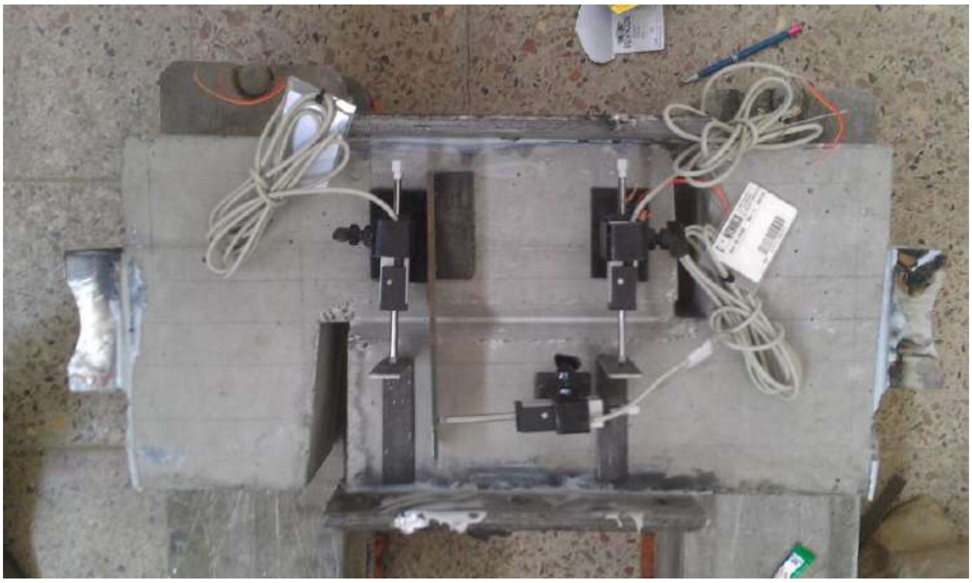


Figure.3. 5: Attaching transducers to the sample

- Placing the sample in the universal testing machine (see Figure.3. 6).

Figure.3. 6: Placing the sample in the universal compression machine for testing

- Testing (see Figure.3. 7).

Figure.3. 7: Testing

3.4. Steel

For the stirrup reinforcement crossing the shear plane use has been made of plane bars of diameter ϕ 6, ϕ 8 and ϕ 10. The stress-strain diagram for the steel is presented in Figure.3. 8.

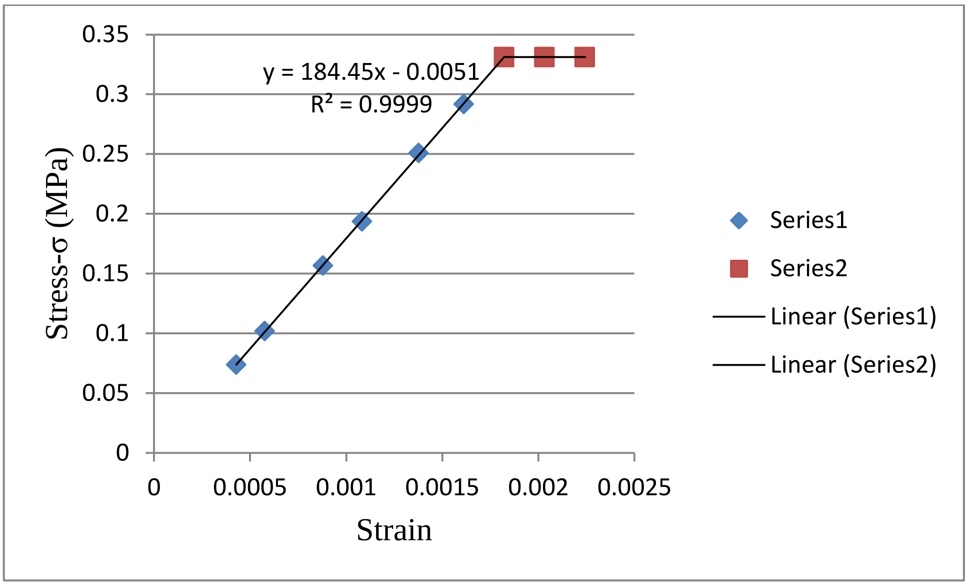
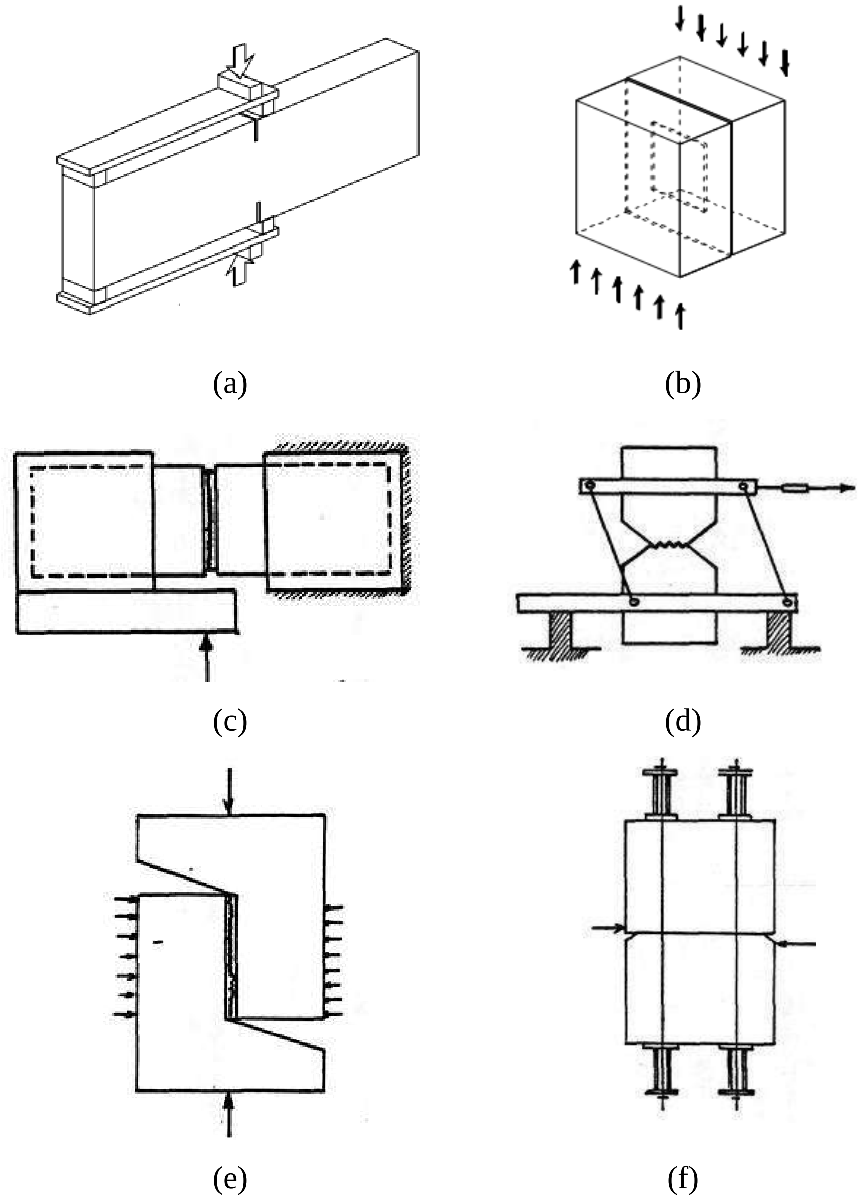


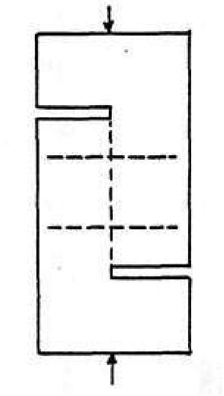
Figure.3. 8: Stress-Strain diagram of transverse bar on the outside

SECTION 4. EXPERIMENTAL PROGRAM

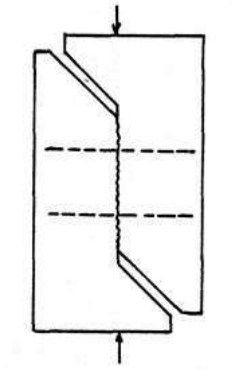
4.1. Choice of the experimental concept

According to Walraven (Walraven, J.C.,Vos.E,Reingardi.H.W.:, 1979) several types of specimens were used over the years by different researchers to investigate interface shear transfer (See Figure.4. 1.)

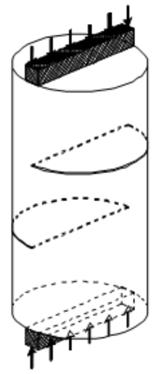




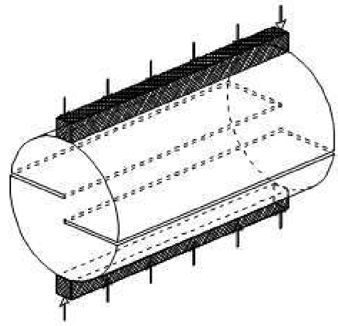
(g)



(h)



(i)



(j)

Figure.4. 1: Experimental arrangements used in previous investigation (Walraven, J.C.,Vos.E,Reingardi.H.W.:, 1979) (Bryan Barragan, 2006)

He further states that "the concept of g and h seemed appropriate for the aim pursued, as it gives the most realistic representation of the object to be studied: a crack crossed by reinforcement and subjected to shear stress". Also, recently, most researchers (Sagaseta, et al., 2011) are using the concept of e and f almost exclusively. The procedure has been refined further over the years. Thus, after considering these points it was decided to use the set up shown in Figure.4. 1-g.

4.2. Refining of test specimen

The test was conducted in two phases.

- Phase-1: Refining of specimen
- Phase-2: Testing using the selected specimen

During the first phase, the arrangement of reinforcement on the head and side of the specimen and the size of the roller bearing plate were investigated.

4.2.1. Refining arrangement of reinforcement in the head and side

Three push-off samples were prepared with three types of reinforcement bar arrangement as shown in Figure.4. 2.

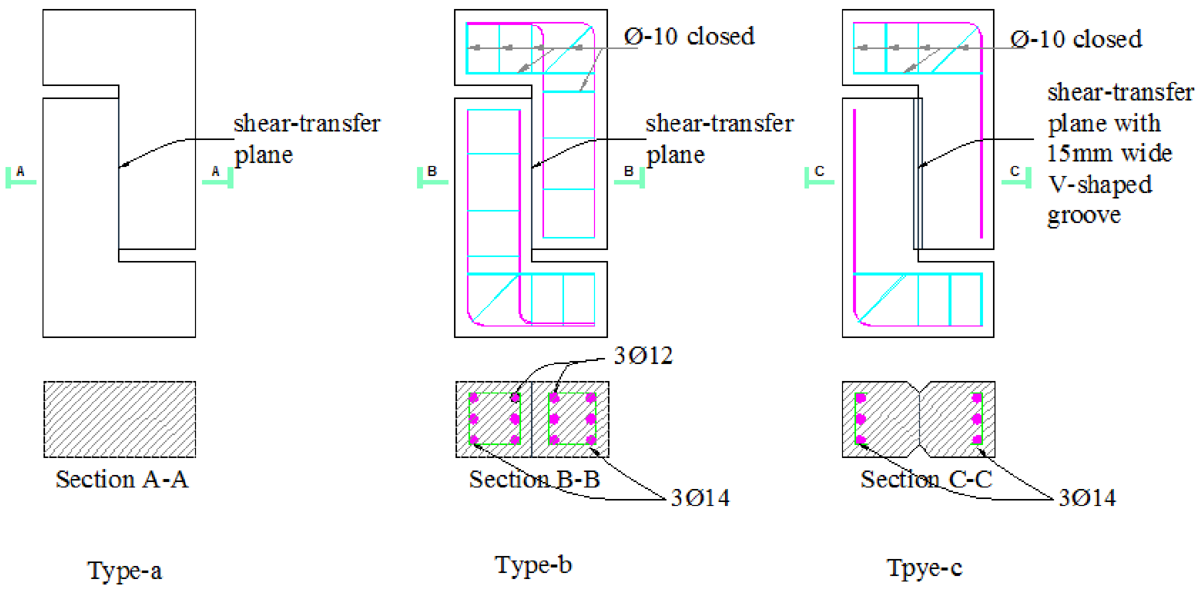


Figure.4. 2: Arrangement of reinforcement on the head and side of specimen

During testing, sample type-a failed prematurely, by flexure, at the connection point between the head and side as shown in Figure.4. 3. This premature failure was attributed to the lack of reinforcement bar in the head and side of the sample.

Figure.4. 3: Sample type a failure

Thus, this sample was replaced by sample type-b which includes 6 ϕ 14 + 6 ϕ 12 bars in the head and side. No premature failure due to flexure occurred during testing. This sample failed by shear around the shear plane. However, the shear crack was not confined to the shear plane as seen in Figure.4. 4. It was also noticed that the longitudinal bars near the shear plane were influencing the way the cracks were formed. This is because the presence of reinforcement bars in the region between the bar and shear plane were mostly filled with mortar not concrete creating a weak region and also with this set up we are more likely to study the behavior of mortar than that of concrete. Thus, to remedy these problems, sample type-c was prepared with two major improvements. First, the longitudinal reinforcement near the shear plane was removed. Second, 15mm wide V-shaped notch was introduced to help confine the shear cracks in the shear plane (see Figure.4. 2, Figure.4. 6, & Figure.4. 7). With these enhancements:

- premature failure is avoided, unlike sample type-a,
- the cracks were confined to the shear plane as shown in Figure.4. 16 & Figure.4. 14 unlike sample type-b and
- only shear cracks are formed.

After considering the above-mentioned points sample type-c was selected for further testing.

Figure.4. 4: Sample type b failure

4.2.2. Refining the size of roller bearing plate

Two sizes of roller plates were also compared. The two plates considered were: 125x100x40mm and 125x40x20 mm. (See Figure.4. 5). No significant difference was noticed between the two types. The 125x40x20 mm was selected to reduce the friction force transferred to the specimen from the universal compression machine.

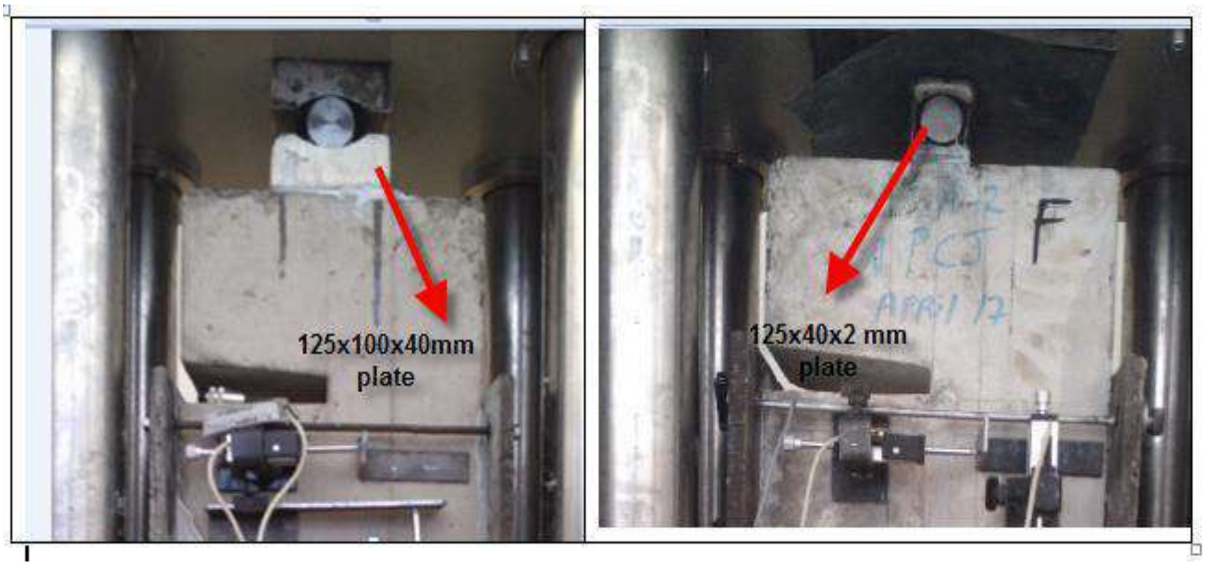


Figure.4. 5: Roller plates

4.3. Scope of the experimental program

In this study, the effect of construction joints on performance of reinforced concrete structural elements is experimentally investigated. In order to properly design the load transfer, provisions are required that

a) Allow for a conservative prediction of the bond capacity between old and new concrete

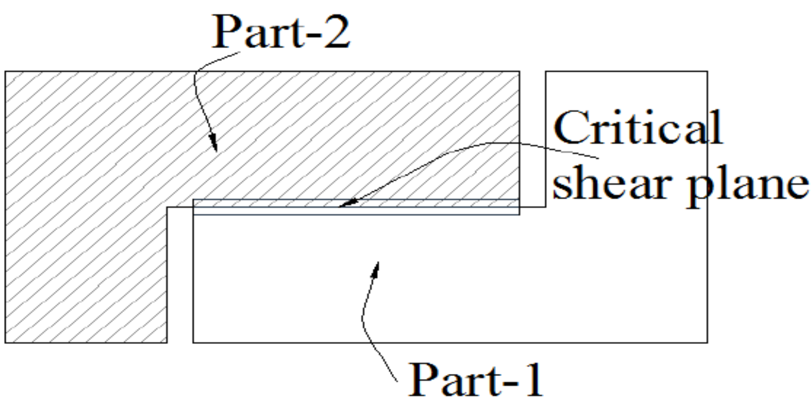
b) Deliver an estimation of the influence of different interface roughness on the load transfer

c) Take in to account the effect of external clamping forces or connectors crossing the interface.

Ten push off samples with dimension of 540mm x 250mm x 125mm with interface shear area of 23,750 mm^2 (250mm x 95mm) were tested. The variables investigated are the influence of age difference, influence of change in the stiffness of external reinforcing bars and influence of surface treatment.

1. **<u>Influence of age difference</u>**

In order to investigate the influence of age difference on interface shear transfer a number of specimens were tested in which the age difference between the two parts was the only variable (see Figure.4. 6). The influence of the age difference was checked for three different stiffness of external bar, where the detail of each approach is elaborated hereunder.



a).

b).

Figure.4. 6: Two parts of the specimen

- <u>Specimen type-1 (Control)</u>

  The two parts of the specimen (part-1 and part-2 in Figure.4. 6.) were placed and vibrated at the same time or monolithically. This would give as, potentially, the interface shear behavior at maximum possible bondage between the two parts.

- Specimen type-2

  The two parts of the specimen were placed 24hrs apart i.e. part-1 is placed and vibrated first and after 24hrs (after the concrete has set and begun to harden) the second part is placed and vibrated. This age difference between the two halves creates a construction joint reducing the bondage between the old and new concrete as compared to specimen type-1. Moreover, no provision of surface preparation and /or treatment were made.

2. **Influence of surface preparation**

- Specimen type-3

  In this specimen, the two parts are placed 24hrs apart like type-2. However this time, after placing and vibrating Part-1 of the specimen, the surface was smoothed with a trowel to see the effect of surface preparation in addition to the age difference on the interface shear transfer strength of concrete. The degree of smoothness of the surface was not quantified and these samples were prepared just to see if the surface treatment has any effect on the interface shear transfer behavior.

3. **Influence of change in the stiffness of external reinforcing bar**

In order to investigate the influence of the stiffness of external reinforcing bars crossing the shear plane, three specimens of varying stiffness were tested. The variation was made by varying the diameter of reinforcement bars as shown below:

- Specimen type-1: with 6 ϕ 6 bars
- Specimen type-2: with 6 ϕ 8 bars
- Specimen type-3: with 6 ϕ 10 bars

Moreover, for each type of stiffness, two types of samples were prepared: one in which the two parts of the specimen were cast monolithically and the other with a construction joint.

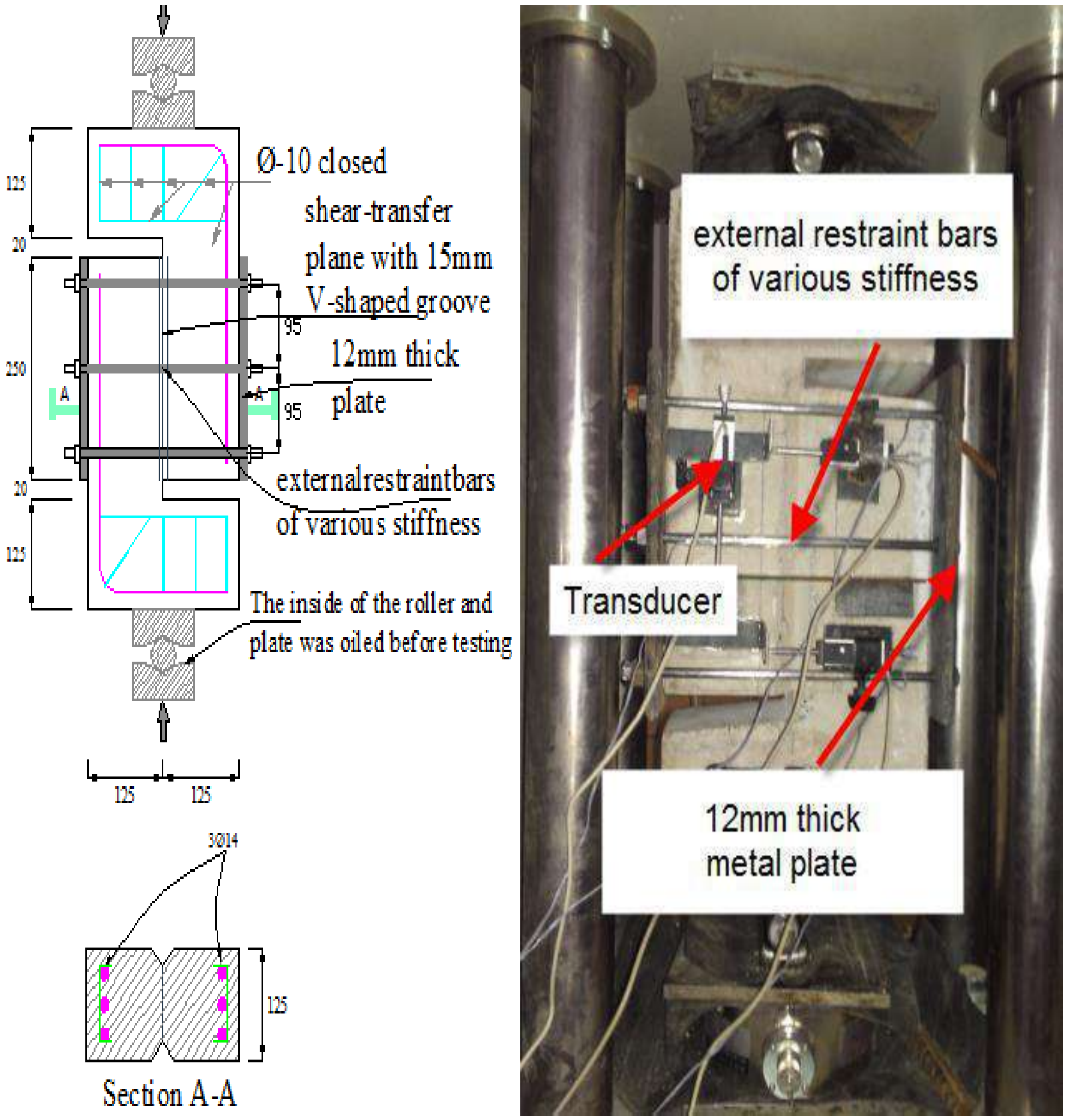
4. <u>To study the influence of placing the bars on the outside</u>

In order to study the influence of placing the reinforcement bar perpendicular to the shear plane on the outside (such a placement was done to avoid potential dowel effect), three types of samples were prepared and their peculiar characteristics are:

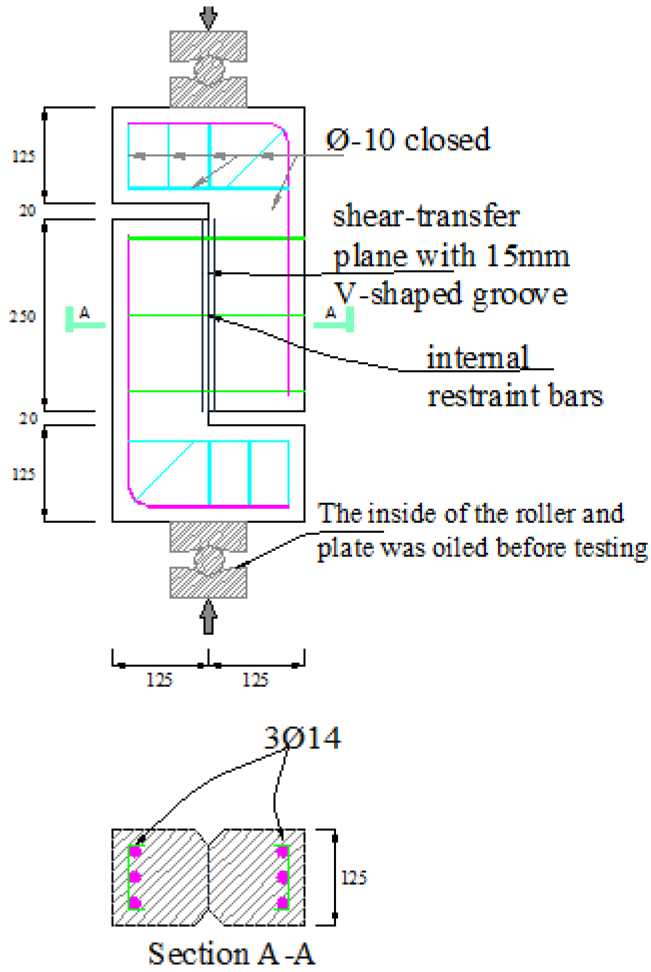
- Specimen type-1: the reinforcement bars crossing the shear plane were placed on the outside as shown in Figure.4. 7 & Figure.4. **8**.
- Specimen type-2: the reinforcement bar crossing the shear plane was placed on the inside.
- Specimen type-3: reinforcement crossing the shear plane was not introduced.

4.4. The test Specimen

The tests were carried out on push off specimens, as discussed in sec 4.1 and 4.2; with external restraint bars of various stiffness. The schematics of the test set-up is shown in Figure.4. 7.



a). specimen with external restraint bars



b). specimen with internal restraint bars

Figure.4. 7: Schematics describing geometry of test specimen

The shear area of all specimens was 23,750mm^2 (250x95mm). A vertical V-shaped notch was made on the shear plane in order to confine the crack to the shear plane as discussed in Sec.4.2. Moreover, the reinforcement bars perpendicular to the shear plane were placed on the outside to avoid dowel effects. This was necessary because the study focuses on effect of construction joint in interface shear transfer and it was believed that dowel action is not affected largely by the presence of construction joint.

On both sides of the specimen, two 12mm thick plates were fixed (one on the left side and one on the right side) to support the external restraint bars. These plates were fixed to the specimen using epoxy as depicted in Figure.4. 8. The epoxy, in addition to fixing the plates to specimen, helps to level the contact area between the plate and the specimen, by filling the opening between the plate and specimen. This greatly reduces the stress lost as the force is transferred from the specimen to the plate as the specimen moves laterally during testing.

As the test progresses, the force in the external restraint bars could be used to restrain the widening of the cracks and/or to compress the concrete between the plates. This is because the concrete could not be rigid enough to transmit the lateral movement from the crack widening directly to the plates. This, in turn, could affect the result since the lateral movement of the crack (widening of the crack) at the shear plane could be compensated by a reverse action of the plate compressing the concrete. In order to measure the lateral compression of concrete by the side plates, a strain gauge was attached to the concrete face between the plates in one of the samples as shown in Figure.4. 9.

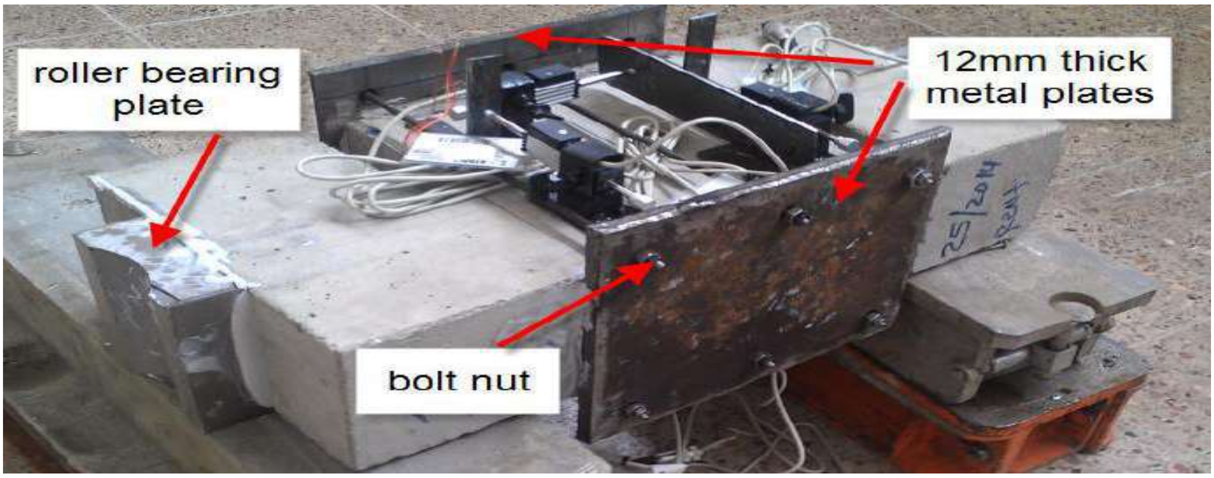


Figure.4. 8: Connection between side plate and specimen

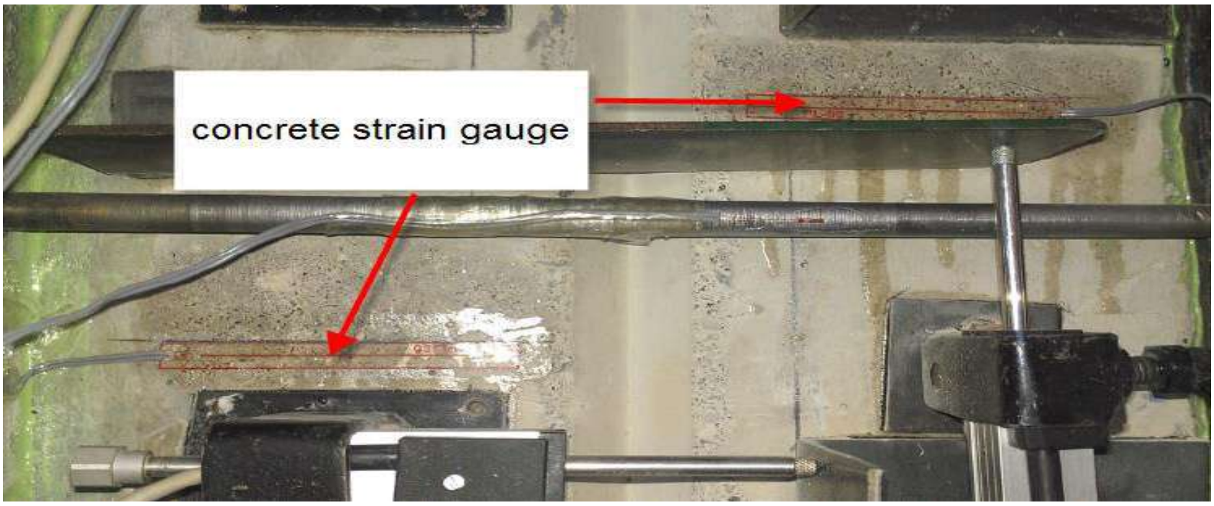


Figure.4. 9: Concrete strain gauge

The external restraint bars were provided with grooves at the end, and they are tapered at the end to compensate for the reduction in diameter during grooving as demonstrated on Figure.4. 10. A bolt was used to prevent the external restraint bars from slipping during testing. This would greatly reduce the stress lost as the force is transferred from the plate to the external restraint bars. The bolts were tightened by hand (no wrench was used). A clear space of about 20mm was provided between the external restraint bars and the specimen, to avoid any contact (friction) between the bar and the specimen.

Figure.4. 10: Geometry of external restraint bar

4.5. Testing arrangements and instrumentation

The tests were carried out using a hydraulic testing machine, to load the specimen along the shear plane, as indicated in Figure.4. 11.

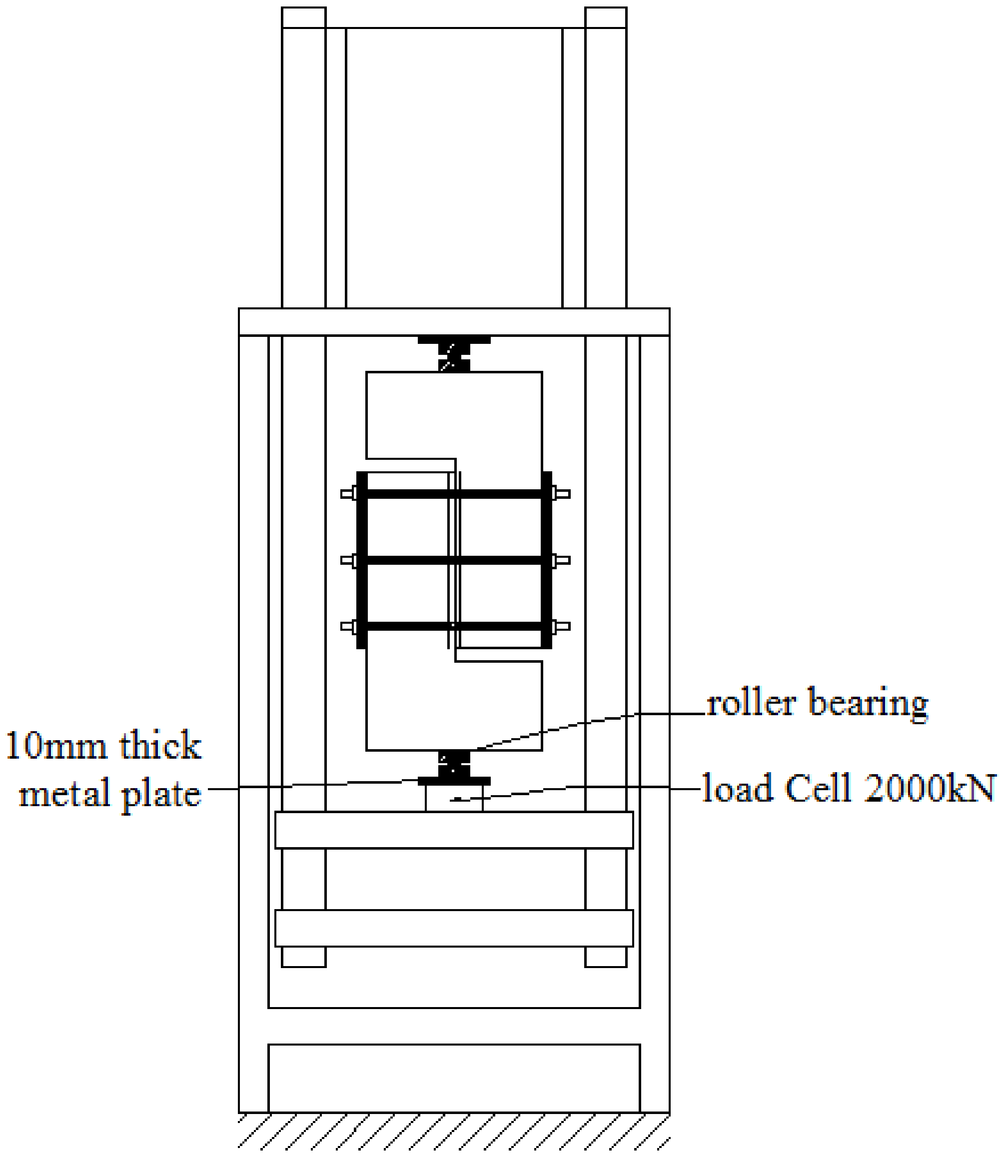
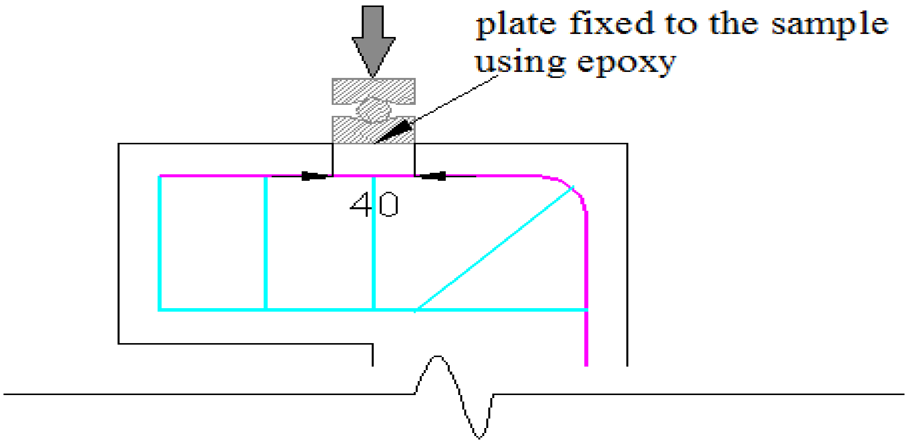
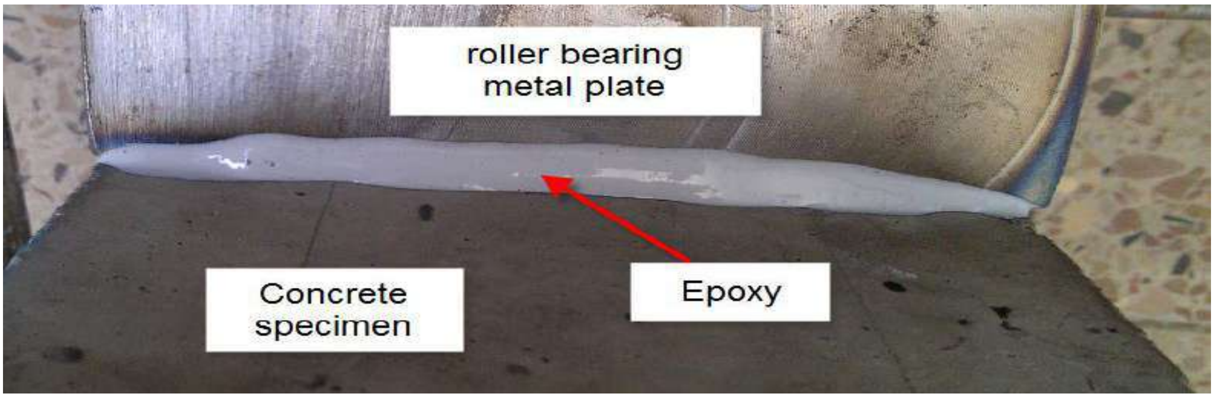


Figure.4. 11: Loading arrangement used for the tests.

The specimen was supported on roller both at the top and bottom (see Figure.4. 7, Figure.4. 11, & Figure.4. 12). Roller support was used to reduce frictional force exerted on the sample by universal compression machine ensuring that separation of the two halves of the push of specimens was not restrained by the machine itself. The rollers and the inside of the plates were lubricated with oil to further reduce the frictional force. The rollers were supported on plates of size 125x40x2mm as discussed in Sec.4.2. The plates were fixed on the concrete specimen using epoxy. The epoxy, in addition to fixing the plates to the concrete specimen, also helps to level the contact area between the plate and sample (by filling the opening between the plate and specimen). This helps distribute the stress uniformly.



a).



b).

Figure.4. 12: Connection of roller plate to the concrete specimen

The specimens were loaded by a vertical load as shown by the arrow in Figure.4. 7. With this method of loading shear without moment is introduced in the shear plane. The specimens were reinforced with L-shaped bars to avoid any other cracks from forming away from the shear plane (see Figure.4. 7).

A load cell was used to measure the vertical external load (see Figure.4. 11, Figure.4. 13). A 10mm thick plate covered with thin rubber was used between the load cell and roller bearing plate in order to distribute the stress uniformly to the load cell.

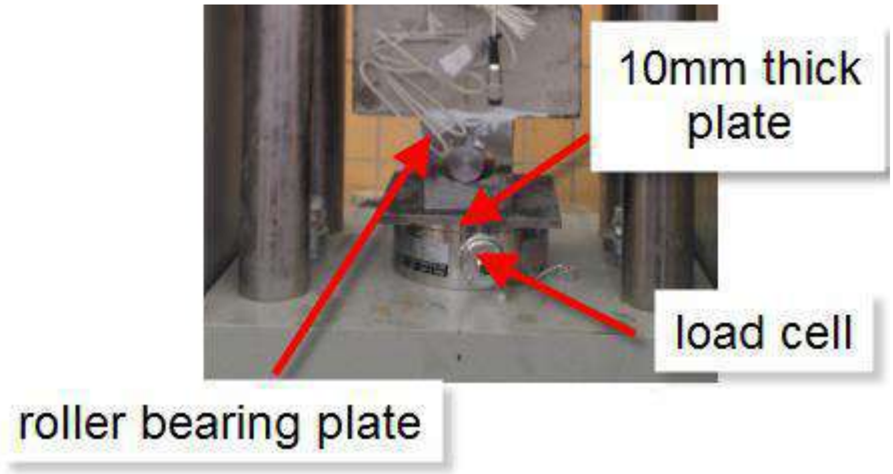


Figure.4. 13: Arrangement of load cell to measure vertical external load

Six transducers (three in front and three at the back) were used to measure crack width and shear slip. These transducers were directly mounted on the specimens and had an accuracy of 0.01mm. On each side (front and back) two transducers (one at the top and one at the bottom of shear plane) were used to measure crack opening and two (one on each side) was used to measure shear slip (see Figure.4. 14)

The aforementioned arrangement was chosen, in addition to measuring crack width and shear slip, to check for the accuracy of the loading. If there is any eccentricity in the loading there would be moment in addition to shear. Depending on the eccentricity the sample, instead of moving vertically and laterally, could open up as shown in Figure.4. 15.

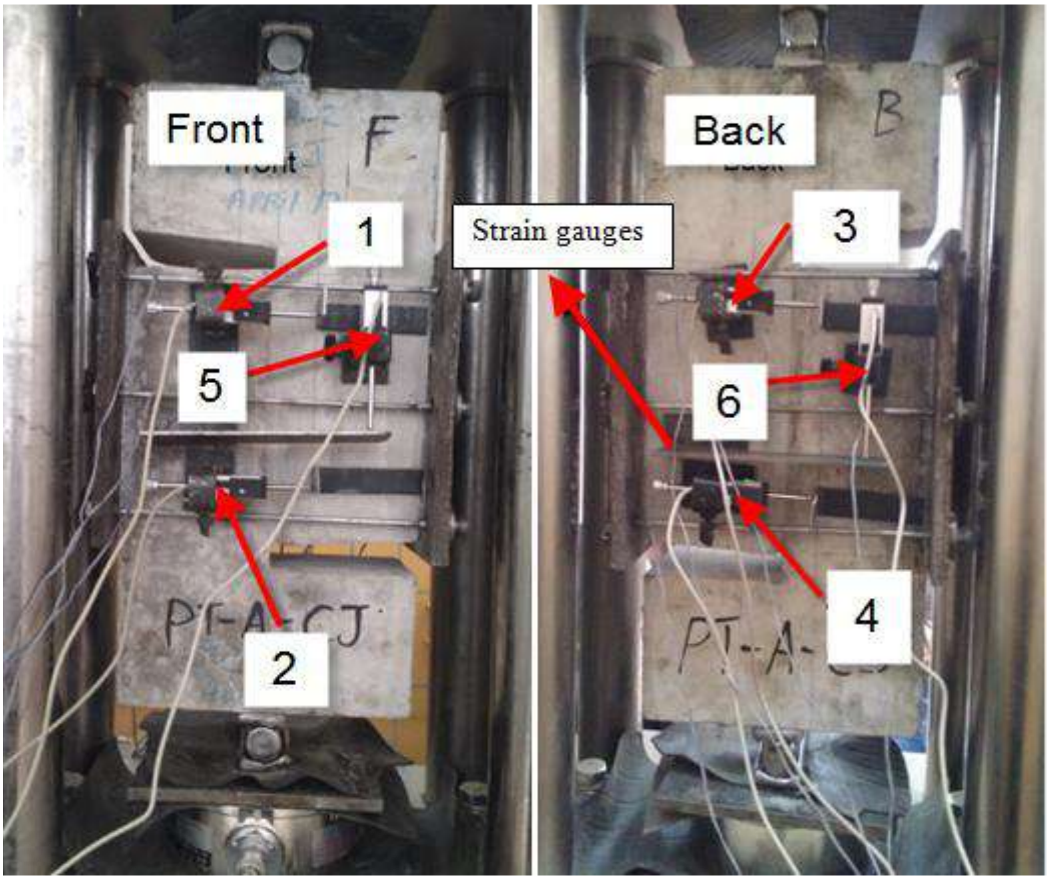


Figure.4. 14: Transducer arrangement to measure crack opening and shear slip

Thus:

- If the sample moved like Figure.4. 15-a, reading of transducers top of the shear plane (transducers marked 1 & 3 in Figure.4. 14) and transducers bottom of the shear plane (transducers marked 2 & 4 in Figure.4. 14) would be different.
- If the sample moved like Figure.4. 15-b, reading of transducers on the front face (transducers marked 1 & 2 in Figure.4. 14) and reading of transducers on the back face (transducers marked 3 & 4 in Figure.4. 14) would be different, ...

Six plus one strain gauges were attached to the six external bars to measure the passive restraint forces normal to the shear plane as shown in Figure.4. 14. The force-strain relationship was established before testing. The external bars are mounted in such a way that only axial force is applied. Two strain gauges were attached on one of the restraining bars to check if the bars are bending during testing.

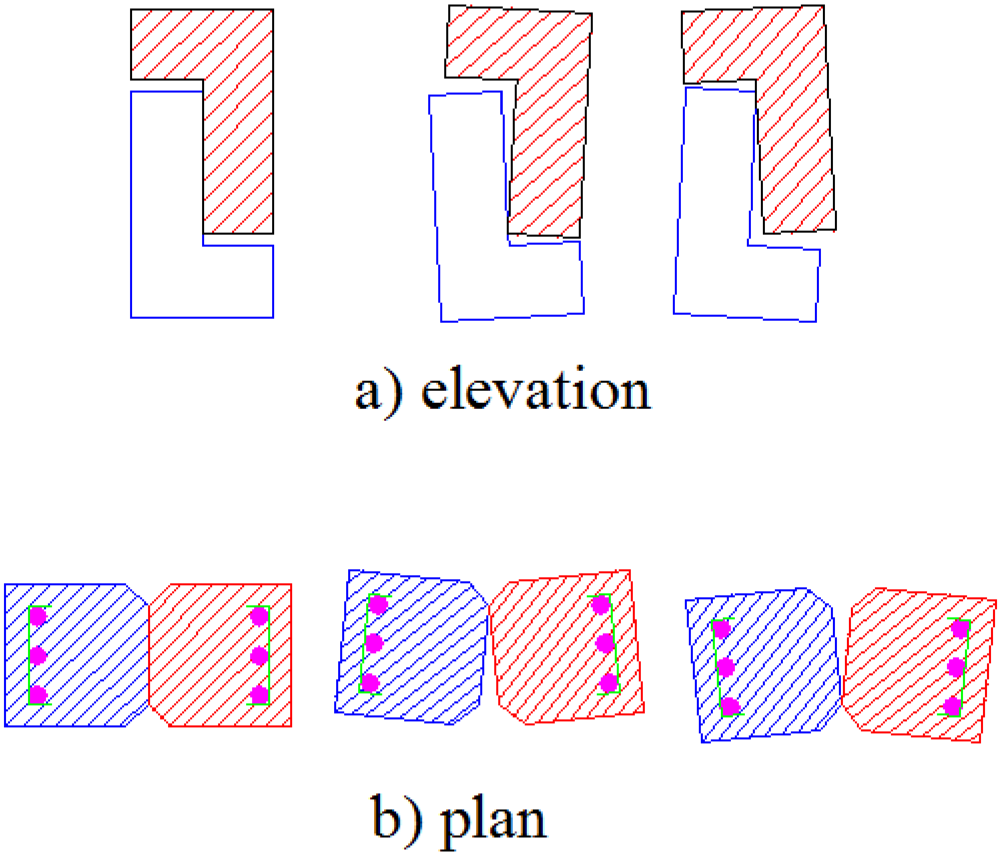


Figure.4. 15: possible movements of specimen parts due to eccentricity

4.6. Testing Procedure

The tests were conducted in two stages:

- First stage-**Before cracking**
- Second stage-**After cracking**

During the first stage, the load was monolithically increased at the rate of 0.04kN/sec, until the specimen cracks at the grooved shear plane. The test was automatically stopped as soon as a crack was visible in the shear plane (see Figure.4. 16).

Figure.4. 16: Cracks formed in the first stage

Then the test was continued again with the same loading rate. The second stage was stopped when the vertical slip reached 20mm. The ultimate load before and after crack was defined as the maximum load carried by the specimen during the test. The shear stress is not uniformly distributed in the shear plane but for simplicity, the average shear stress is calculated by dividing the shear force by the shear plane area. All data measured by the transducers were collected in.CSV format. Two data logers were used one for the transducers and one for the strain gauges and load cell (see Figure.4. 17).

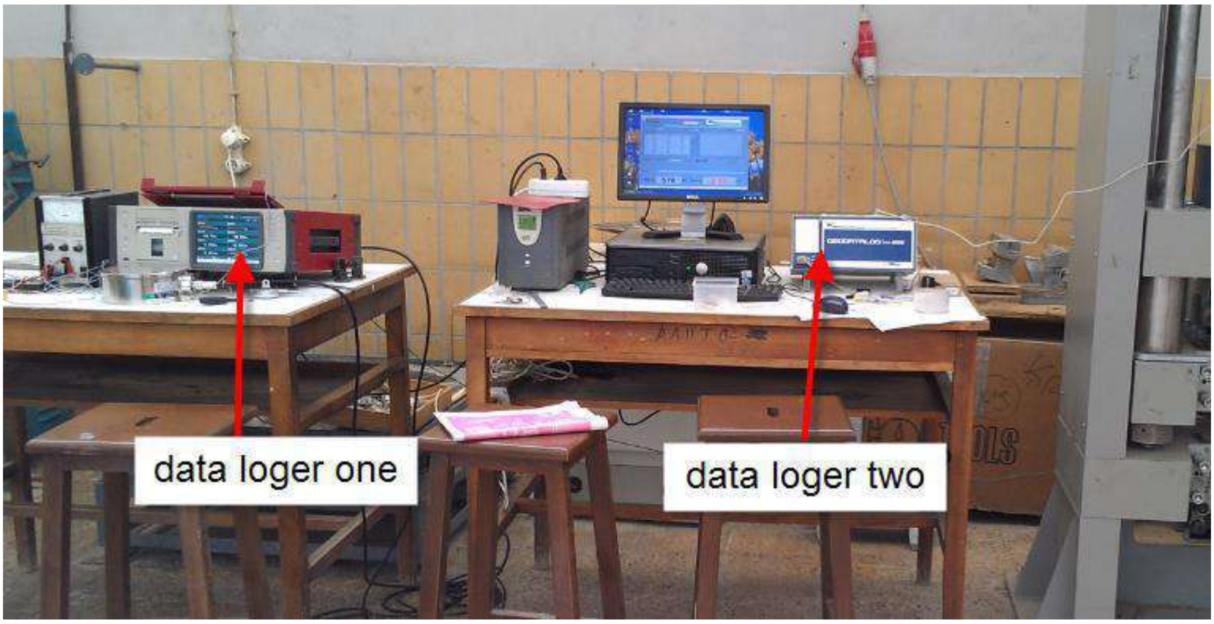


Figure.4. 17: Data logers used to collect data during the test

SECTION 5. TEST RESULTS AND DISCUSSION

5.1. Codification

All specimens have been assigned an identifying code indicating the type of the specimen. The symbols representing these data are separated by hyphens (-). The first letter indicates that the test is push-off test. The second letter indicates the diameter of the stirrup crossing the shear plane. Four types of diameters of stirrup were used:

- A is for ϕ 6mm
- B is for ϕ 8mm
- C is for ϕ 10mm
- D no stirrup crossing the shear plane

The third letter indicates whether the two parts of the specimen were cast monolithically or 24hrs apart (see Figure.4. **6** and section 4.3).

- **M** is for Monolithically cast
- **CJ** is for construction joint

The last number indicates that the reinforcement crossing the shear plane is on the outside or on the inside (See Section 4.3 and Figure.4. 7).

- **01** is if the reinforcement crossing the shear plane is on the outside
- **02** is if the reinforcement crossing the shear plane is in the inside

A full survey of all tests with a detailed description of the variables and results is given in Table 5. 1

Table 5. 1: Test specimens

Specimen Type	Code	Weight (Kg)	C.Strength (Mpa)	reinforcement bar crossing the shear plane							ultimate shear strength (Mpa)		Remark
				size (mm)	number	ρ (%)	Fu BC**	ρf (Mpa)	Fu AC**	ρf (Mpa)	before crack	after crack	
PT-A	PT-A-M-01	39.55	31.08	6	6	0.71%	4.40	0.031	35.54	0.254	2.91	2.12	
	PT-A-CJ-01	40.15		6	6	0.71%	5.29	0.038	207.60	1.483	2.36	2.57	
	PT-A-CJ-01*	39.93		6	6	0.71%	3.04	0.022	152.00	1.086	1.91	2.47	
PT-B	PT-B-M-01	40.06	28.87	8	6	1.27%	4.86	0.062	42.18	0.536	2.97	3.35	
	PT-B-CJ-01	39.49		8	6	1.27%	1.23	0.016	36.83	0.468	2.65	3.65	
PT-C	PT-C-M-01	39.58	29.03	10	6	1.98%	4.89	0.097	61.02	1.211	3.06	3.91	
	PT-C-CJ-01	39.7		10	6	1.98%	3.97	0.079	9.04	0.179	2.17	2.12	
PT-D	PT-D-CJ-01	40.01	34.43	-	-	-	-	-	-	-	5.00	-	
PT-A	PT-A-M-02	41.05	41.83	6	6	0.71%	-	-	354.00	2.529	5.63	2.96	
	PT-A-CJ-02	40.01		6	6	0.71%	-	-	354.00	2.529	4.00	2.66	

* the surface was smoothed with trowel after placing the first part

Fu BC** is ultimate confinement force before crack

Fu AC** is ultimate confinement force after crack

5.2. Presentation of results

All measurements have been presented in graphs using Excel sheets. The units of measurements and specimen codes are included in all the graphs. The relations presented in the graphs are:

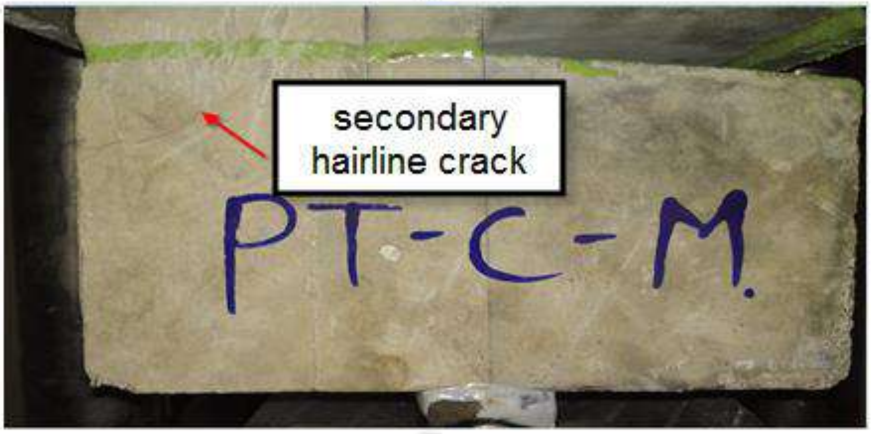
1. The average shear stress on the shear plane as a function of the average shear displacement (Shear slip-Δ)
2. The average shear stress on the shear plane as a function of the average crack width (crack opening-W)
3. Crack opening path (the relation between the shear slip and widening)
4. The average shear stress on the shear plane as a function of the average confinement force in the external restraint bars crossing the shear plane.

All relations have been represented twice, both for before and after the formation of cracks in the shear plane.

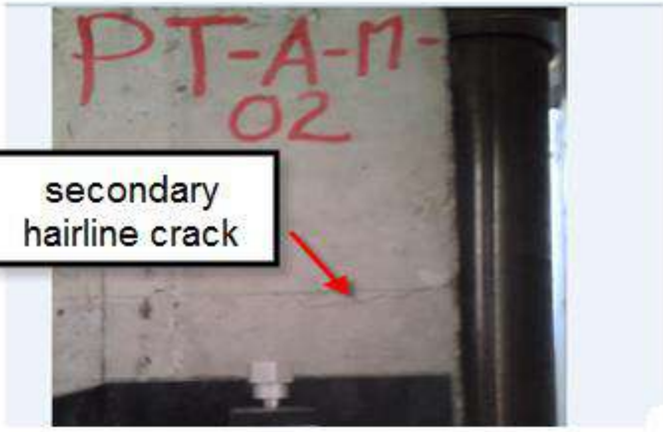
5.3. Observations during the tests.

In two of the samples (PT-C-M-01 and PT-A-M-02) secondary cracks were observed during testing (see Figure.5. 1). This is mainly due to larger shear stress in the shear plane due to the relatively larger degree of confinement. The secondary cracks were hairline cracks and their width didn’t increase throughout the test. Both these samples failed by shear cracks in the shear plane.

Testing of sample PT-C-M-01 had to be repeated because the test was stopped accidentally during the test. No visible cracks were formed at this stage and hence, the test was simply continued by reloading again.



a) PT-C-M-01



b). PT-A-M-02

Figure.5. 1: Secondary Cracks

The test for sample PT-A-M-02 had to also be repeated because the sample rotated during testing (see Figure.5. 2). This was mainly due to a mistake made in attaching the top roller support to the concrete sample. This mistake introduced a large eccentricity which caused the sample to rotate. No visible cracks were noticed before the sample rotated. The top roller support was removed and attached again correctly and the test was continued by reloading again.

In all the tests vertical cracks were formed in the shear plane. Slight deviations (spalling) were also noticed in almost all the samples. These deviations were because the vertical propagation of the cracks was disturbed by the presence of oversized coarse aggregates in the shear plane. It was also noticed that in many of the samples the coarse aggregates were broken during the test.

Figure.5. 2: Rotated Sample PT-A-M-02

5.4. Discussion of results

To understand how the presence of a construction joint could affect the interface shear strength, a number of tests were conducted with and without construction joints in the shear plane (shear interface). To better understand the effect of construction joint the tests were conducted under different conditions, which are:

1. Under different levels of confinement across the shear plane
2. With external and internal confinement bars across the shear plane.
3. For different surface treatment

The effect of the construction joints under the above-mentioned conditions was done before a crack was formed in the shear plane and after. This distinction was made because the machine used was load controlled and would stop automatically once a crack was formed in the shear plane, making it impossible to study the post-peak behavior. Thus the study was divided in to before and after formation of crack with emphasis given to before crack is formed.

In all the tests conducted a major reduction in the shear strength is noticed because of the presence of construction joint. Shear strength reduction up to 35% is noticed, see Figure.5. 3.

5.4.1. Test result and discussion before a crack is formed in the shear plane

In this stage, it was observed that both the vertical (slip) and horizontal (separation) movement of the sample was very small. Because of these small movements the bars crossing the shear plane on the outside didn’t provide that much confinement to the samples (see Table 5. 1,Figure.5. 3 and Figure.5. 4). This resulted in relatively smaller shear strength before crack is formed in the shear plane.

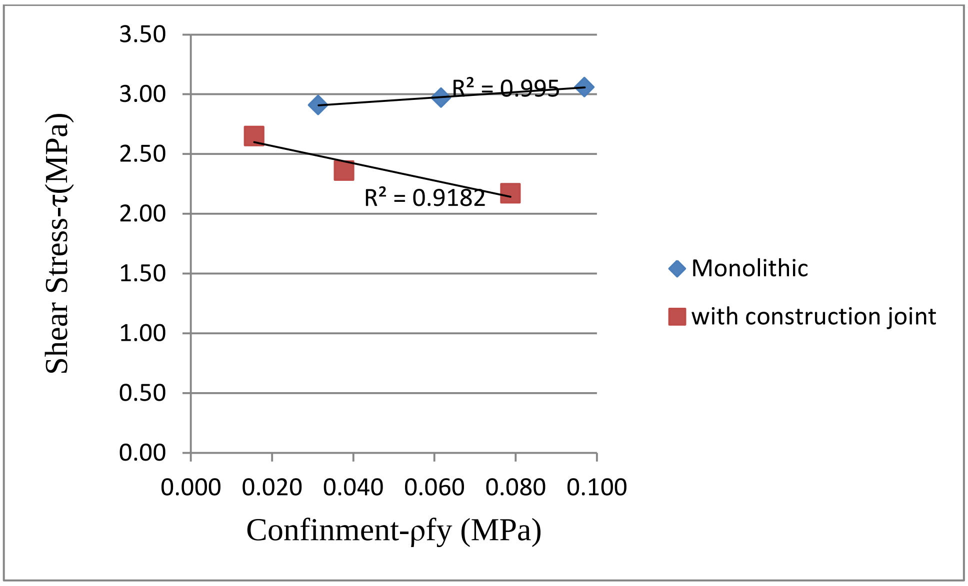


Figure.5. 3: Variation of shear strength with reinforcement parameters with and without construction joints before a crack is formed in the shear plane

1. <u>The influence of construction joint (for different levels of transverse confinement)</u>

A number of tests were conducted with and without construction joints in the shear plane for different levels of transverse confinement. This was done to see if the effect of construction joint could be counteracted by providing large transverse confinement bars.

A total of seven tests were conducted with different levels of confinement bars (with external bars). One sample was tested with no external confinement (ρ = 0%). Two samples each (one with and one without construction joint) were tested with 6 Ø 6 bars (ρ = 0.71%), 6 Ø 8 bars (ρ = 1.27%) and 6 Ø 10 bars (ρ = 1.98%). The results of these comparisons are represented in Table 5. 1, Figure.5. 4 and Figure.5. 6.

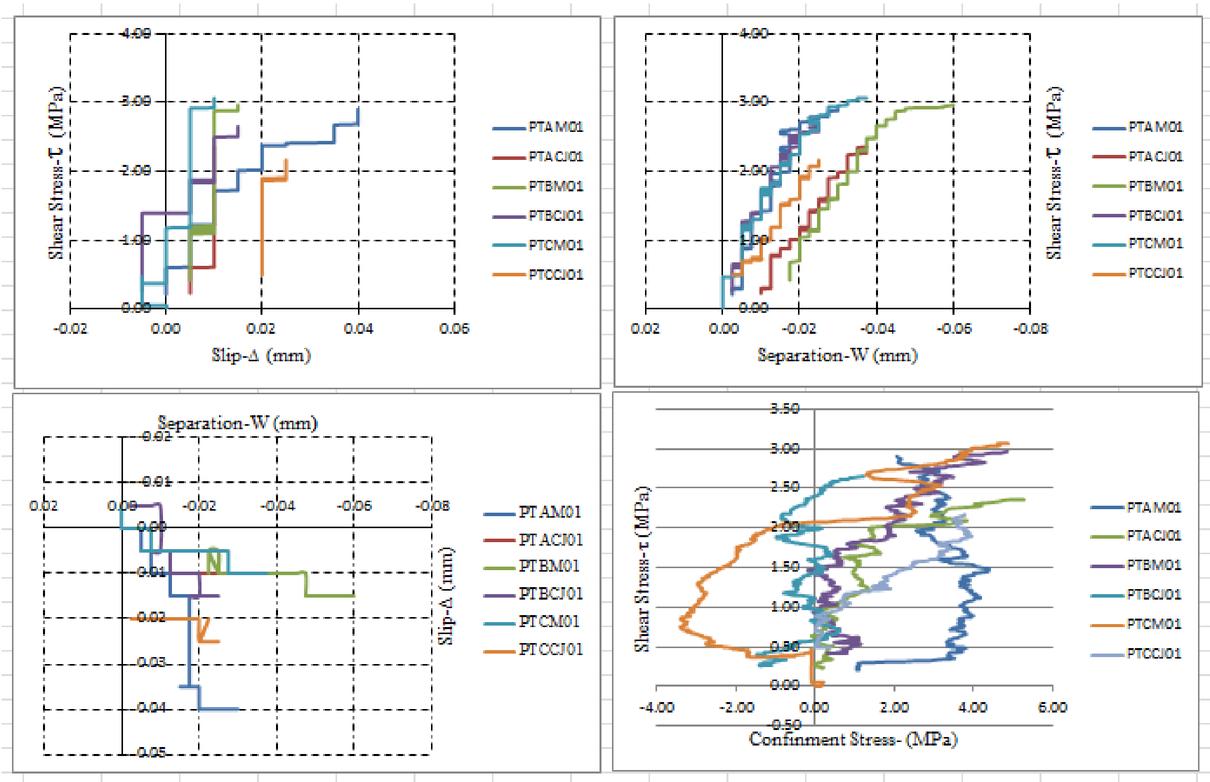
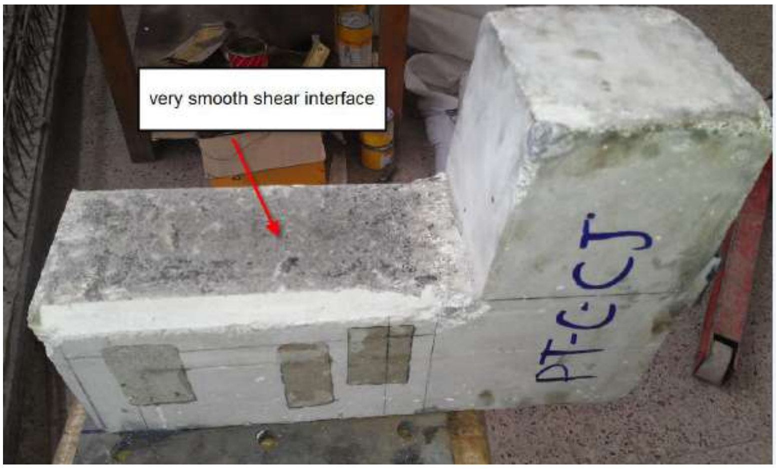


Figure.5. 4: The effect of construction joint for different levels of confinement before crack

It can be seen that in all cases the results are not smooth. The graphs depict a step-wise increase in both the slip and separation. This step-wise increase is attributed to two factors. First, this is because the external transverse bars were not highly efficient in providing confinement (please see below-influence of construction joint with external and internal confinement bars for further explanation). Second, because of the sensitivity (precision) of transducers used.



a). PT-C-CJ-01

c). PT-A-CJ-01*

Figure.5. 5: Comparison of shear interface plane for PT-C-CJ-01 and PT-A-CJ-01*

The results of Table 5. 1, Figure.5. 3,Figure.5. 4 and Figure.5. 6 shows that as the area of steel crossing the shear plane (ρ) increases the shear strength of both samples with and without construction joint increases. The shear strength of the monolithic samples increased from 2.91 MPa to 2.97 MPa to 3.06 MPA and the shear strength of samples with construction joint generally increased from 2.36 MPa to 2.65 MPa. The result of PT-C-CJ-01 was noticed to be very small and this was caused by the relative smoothness of the shear interface plane. The relative smoothness of this sample was caused because it was over vibrated during casting (see Figure.5. 5). The results of this sample is very close to PT-A-CJ-01* which was intentionally polished to give it a smooth interface in the shear plane.

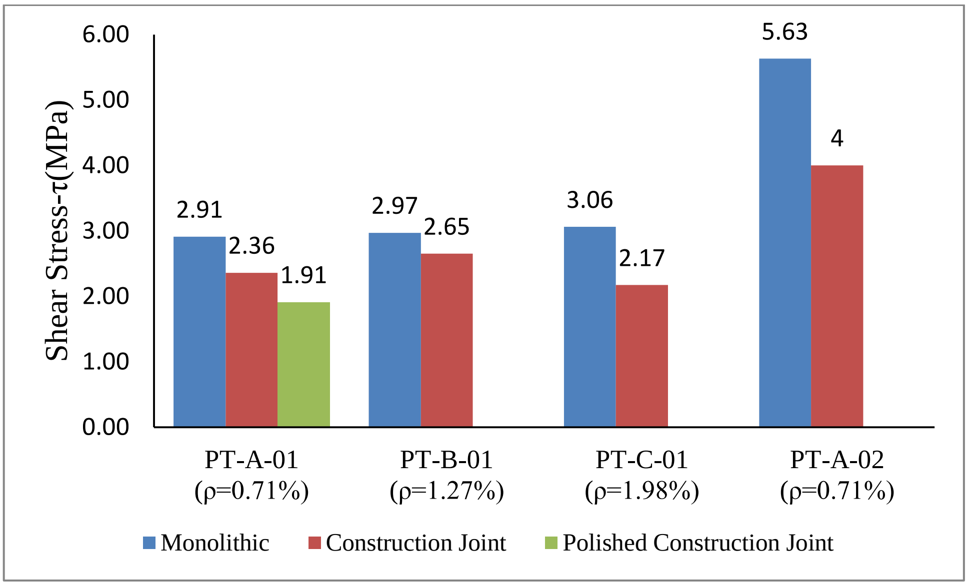
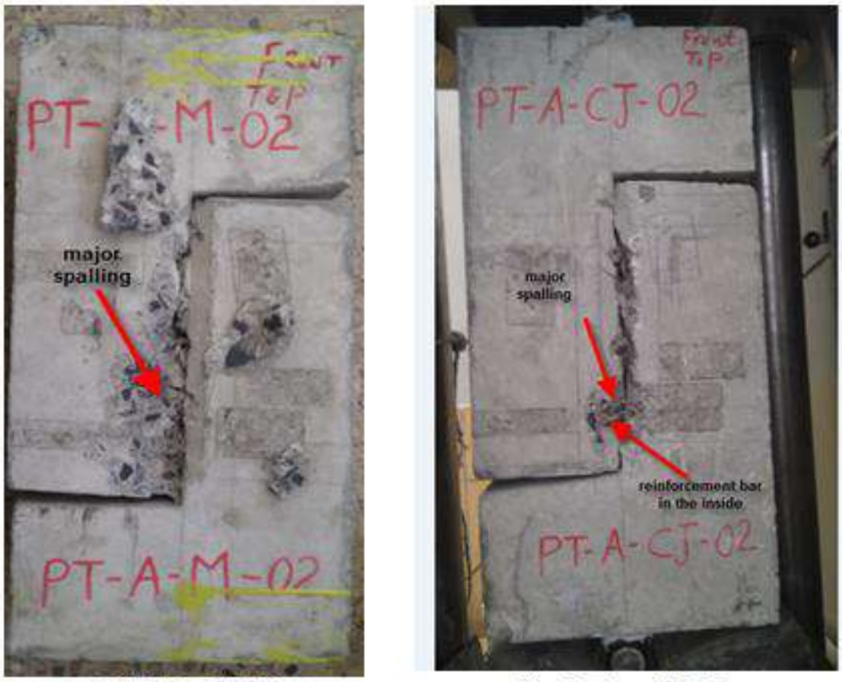


Figure.5. 6: Results of test result to show the effect of construction joint before crack

In summary, we can say that the reduction in shear strength could be counteracted by providing larger transverse bars (confinement bars).



a). PT-A-M-02 b). PT-a-CJ-02

Figure.5. 7: Major spalling for samples in which the confinement bars were placed in the inside

2. <u>The influence of construction joint (with external and internal confinement bars)</u>

To understand how putting the confinement bars (reinforcement bars crossing the shear plane) on the outside could affect the interface shear strength two more samples (with and without construction joint) were prepared with the confinement bars placed on the inside. A major spalling was noticed during testing for these two samples (see Figure.5. 7). This major spalling is because of the bending of the reinforcement bar crossing the shear plane-dowel action. The results of these comparisons are shown in Table 5. 1, Figure.5. 6 and Figure.5. 8 From these graphs we can see three major points.

- The graphs are a lot smoother when the confinement bars are placed in the inside (embedded in the concrete).
- The shear strength has also increased greatly when the confinement bars are placed in the inside. For the monolithic case shear strength has increased from 2.91 MPa to 5.63

MPa (93% increase) and for samples with construction joint, the shear strength has increased from 2.36 MPa to 4 MPa (70% increase). This increase in shear strength is due to the larger degree of confinement provided when the bars crossing the shear plane are placed in the inside. This increase in confinement force is:

- Because when the confinement bars are embedded in the concrete additional strength is developed due to the bond between the concrete and reinforcement bar.
- Because when the bars are embedded in the concrete additional shear strength is developed due to dowel action.
- Because when the confinement bars are placed on the outside they are connected to the plates using bolts and the plates to the sample using epoxy. However, care is taken in connecting the bolts and plates the confinement capacity of the system is going to be reduced due to the relative movements of the different parts.

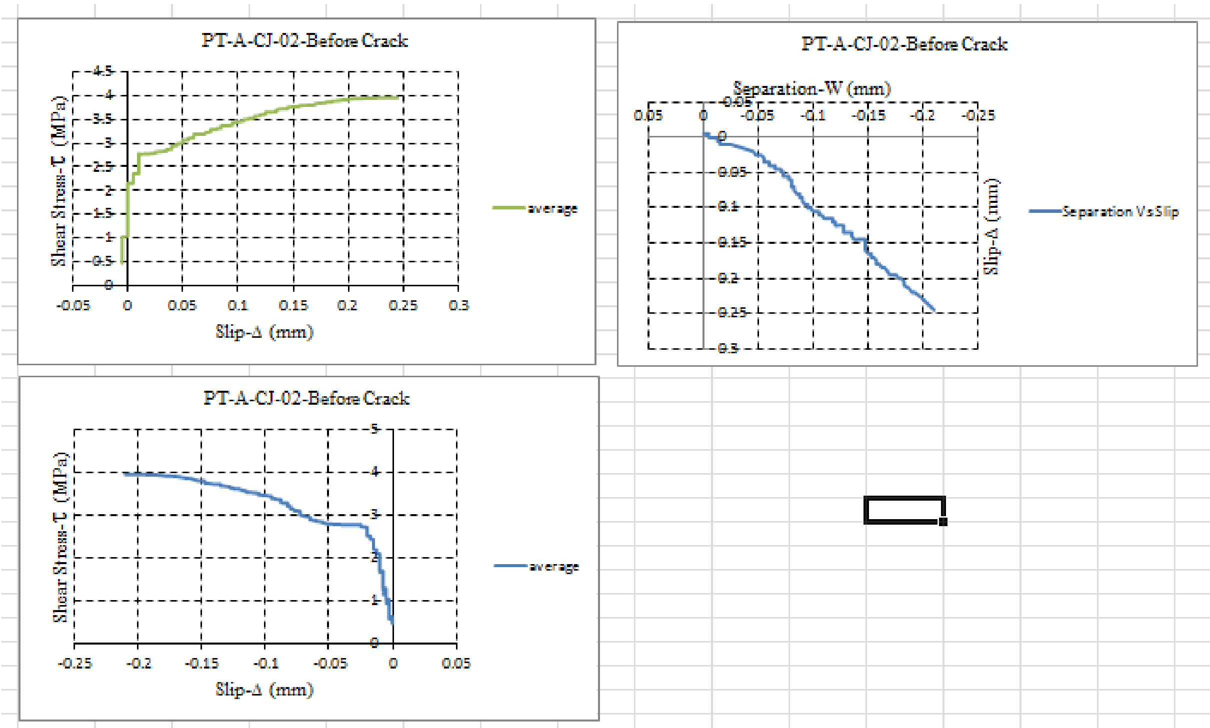
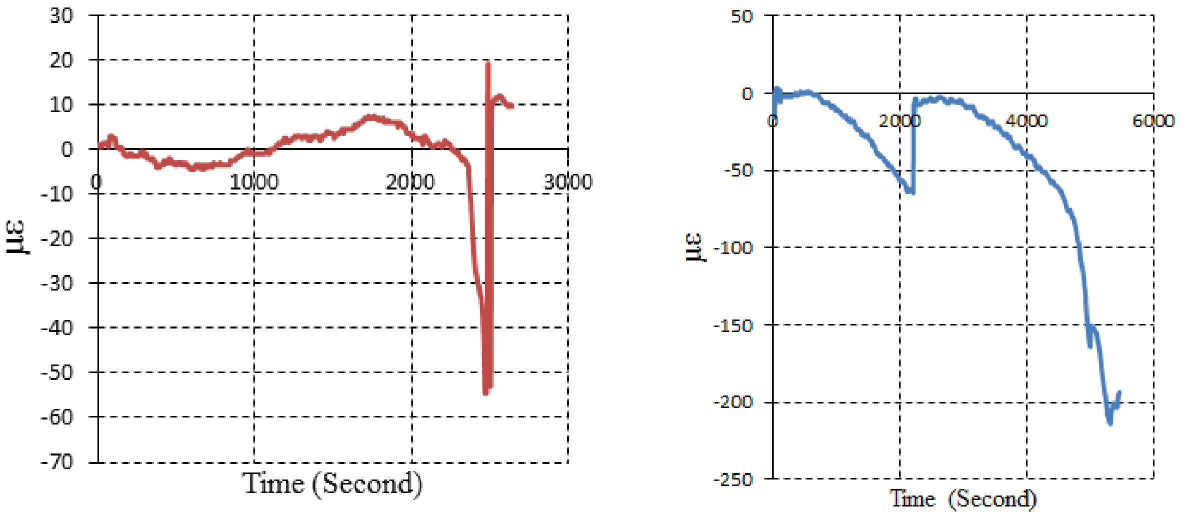


Figure.5. 8: Results for confinement bar in the inside

During testing the force in the external restraint bars could be used to restrain the widening of the cracks and/or to compress the concrete between the plates. This is because the concrete could not be rigid enough to transmit the lateral movement from the crack widening directly to the plates. This, in turn, could affect the result because the lateral movement of the crack (widening of the crack) at the shear plane could be compensated by the plate compressing the concrete in between the plates.To check how much the concrete is being compressed by the plates a strain gauge was attached to the concrete face between the plates in one of the samples (see Figure.4. 9).

As can be seen from Figure.5. 9 the strain in the concrete is very small (change in length at ultimate load is around 20µm). This means the concrete between the plates is not being compressed much by the external plates.



a) Concrete Strain Before Cracking

b) Concrete Strain After Cracking

Figure.5. 9: Strain reading for concrete between the side plates

3. <u>The influence of construction joint (with surface treatment)</u>

During the preparation of the samples with construction joints the two halves were cast 24 hrs. apart. Generally, no surface treatments were made before placing the second part. But, in one of the samples, the substrate concrete was smoothed by trowel (during casting while the substrate concrete is still wet) to see the effect of surface treatment on the interface shear strength. The results of these comparisons are presented in Figure.5. 6 and Table 5. 1.

a). PT-A-M-01

b). PT-A-CJ-01

c). PT-A-CJ-01*

Figure.5. 10: The effect of surface treatment on the interface shear strength

We can see from the results that surface treatment could have a major effect in the interface shear strength. This reduction is mainly due to the reduction in the aggregate interlock forces because of the relatively smooth interface between the two faces of the shear plane (see Figure.5. 10.).

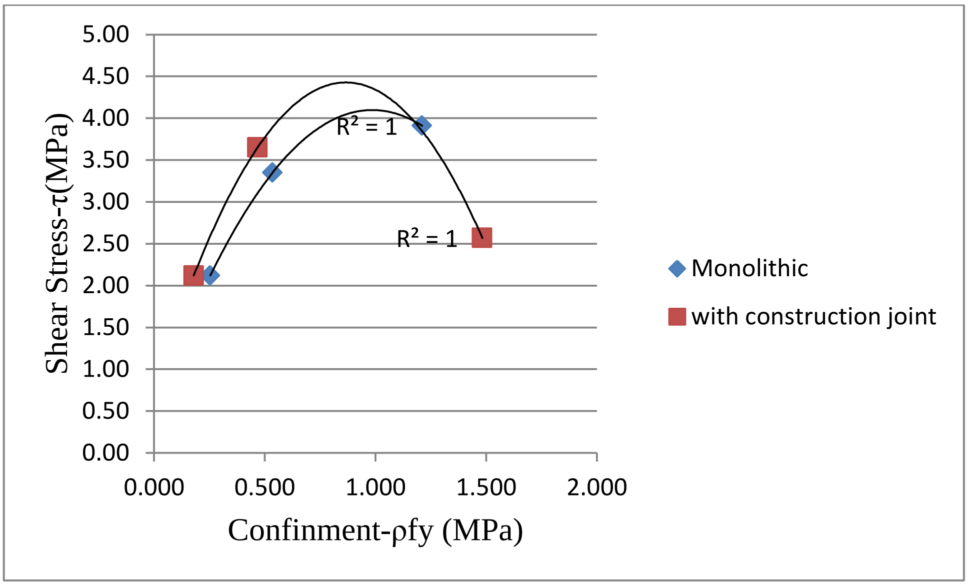


Figure.5. 11: Variation of shear strength with reinforcement parameters with and without construction joints after a crack is formed in the shear plane

5.4.2. Test result and discussion after a crack is formed in the shear plane

After the formation of cracks in the shear plane, there was measurable movement both in the vertical (slip) and transverse (separation) direction. This resulted in an increase in the confinement force provided by the transverse bars. As can be seen in Figure.5. 12 and Figure.5. 13 the shear strength of the samples increased after the formation of cracks due to the increase in transverse confinement force.

After the formation of the cracks, a much more defined and smooth graphs were also observed. This is associated with the relatively larger confinement provided by the transverse bars after the formation of crack in the shear plane (see Figure.5. 12).

After the formation of the crack (as can be seen in Figure.5. 11, Figure.5. 12 and Figure.5. 13) it was generally observed that the samples with construction joint had a better shear resisting capacity for low degree of confinement and the monolithic samples showed a larger shear capacity for larger degrees of confinement.

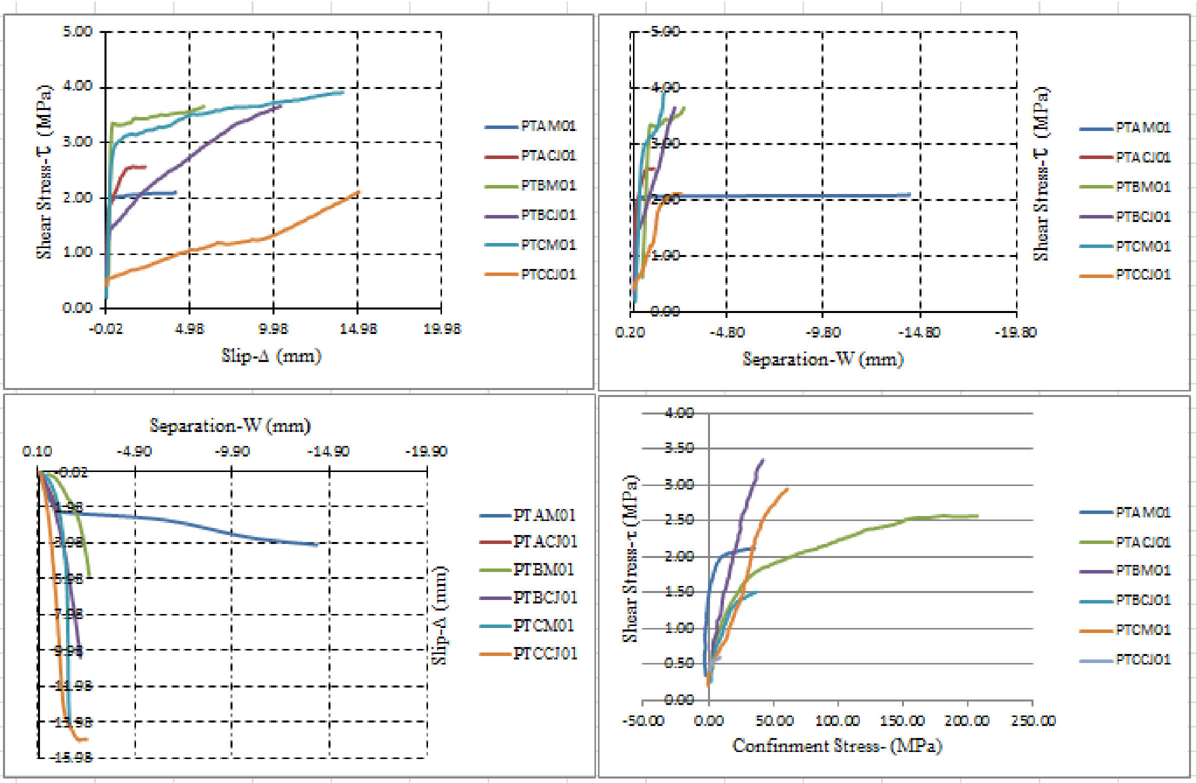


Figure.5. 12: The effect of construction for different level of confinement after crack

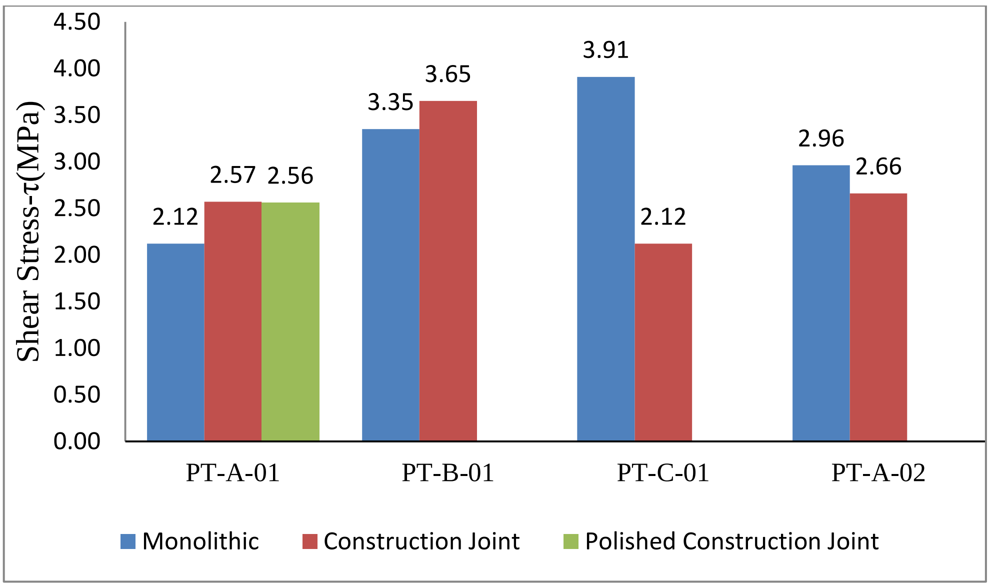


Figure.5. 13: Results of test result to show the effect of construction joint after crack

5.5. Comparison of experimental results with major models and codes

The experimental results were compared against shear interface models proposed by different researchers and building codes. These models were summarized in section two. The results of these comparisons are presented in Figure.5. 14 and Figure.5. 15. For both before and after cracking the results by the building codes are very conservative for both samples with and without construction joint.

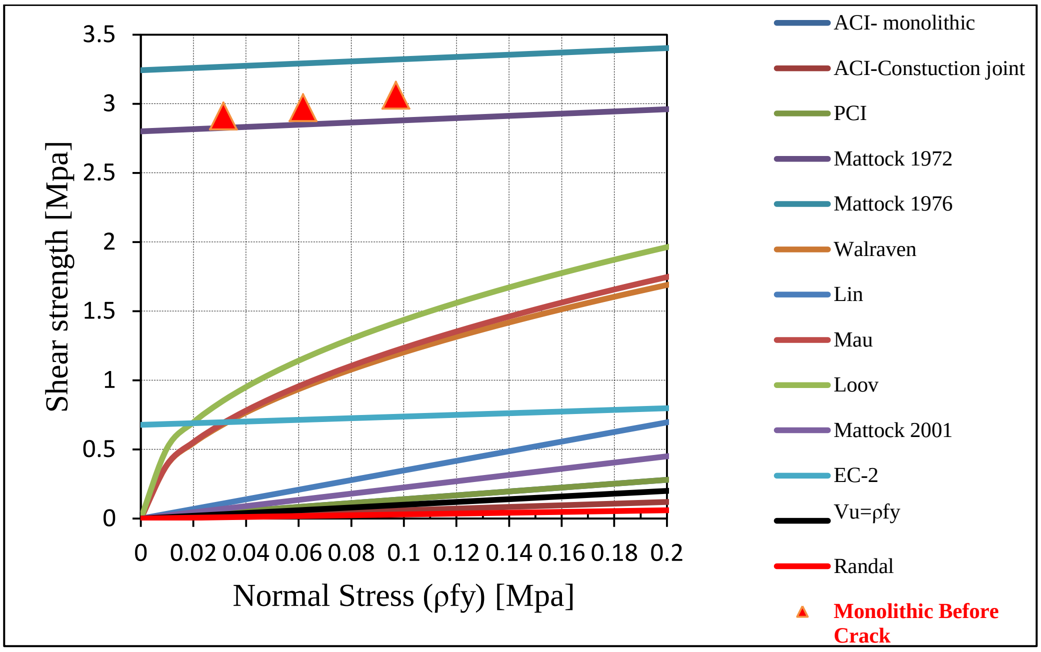
As can be seen from Figure.5. 14 the model proposed by Mattock (Mattock, et al., 1976) and (Mattock,A,H, and Hawkins,N,M.,, 1972) fit almost perfectly with the experimental results. The similarities between this model and experimental results were mainly due to the following reasons:

- This model is developed for monolithic samples
- The model includes a cohesion factor-and for monolithic samples before cracking the contribution of cohesion to the interface shear strength is large because of the relatively small slip at the shear plane.
- There is a great deal of similarities between the specimens used in the current study and that used by Mattock (Mattock,A,H, and Hawkins,N,M.,, 1972) (Mattock, et al., 1976)

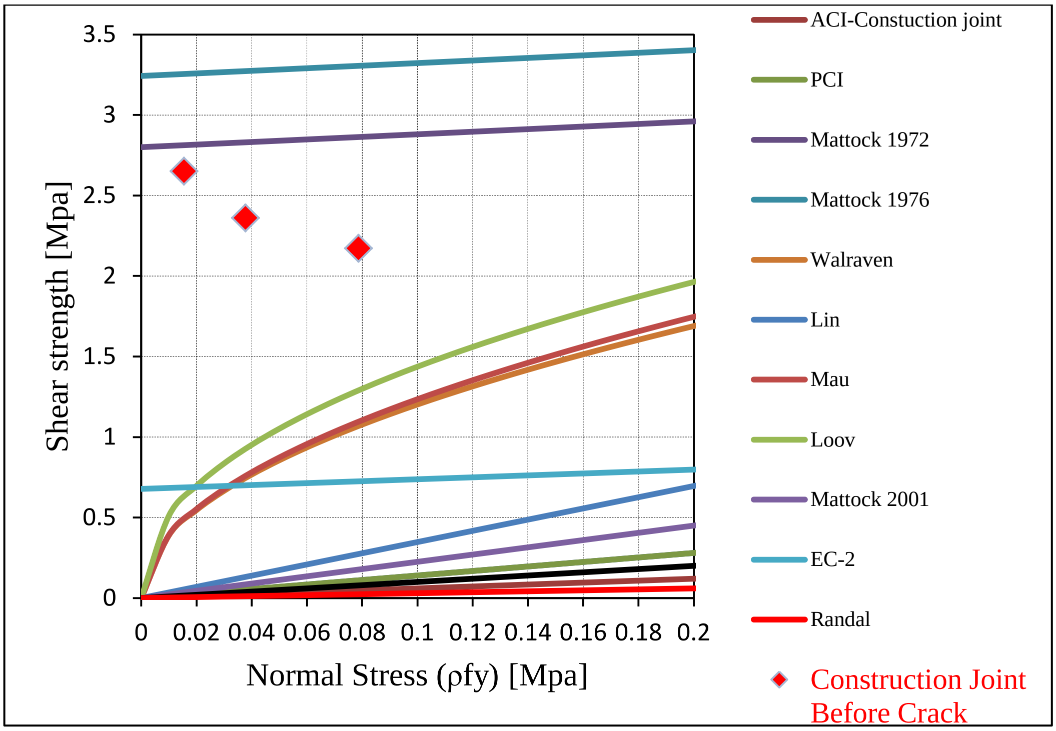
But after the formation of cracks in the shear plane the experimental results, as can be seen from Figure.5. 15, are better explained by the model developed by Walraven (Walraven, 1980). The similarities between this model and the experimental results were mainly due to the following reasons:

- This model is developed to predict the shear strength of initially cracked interfaces.
- The confinement for the experiment is similar to that used by Walraven (Walraven, 1980) for developing the model.

The experimental results for the samples with construction joint do not fit to a particular model for both before and after formation of cracks. This is to be expected as most of the models are developed for samples with and without cracks and not for samples with construction joints. But the prediction by the above-mentioned models by Mattock (Mattock,A,H, and Hawkins,N,M.,, 1972) and Walraven (Walraven, 1980) are still not far from the experimental results with construction joints.

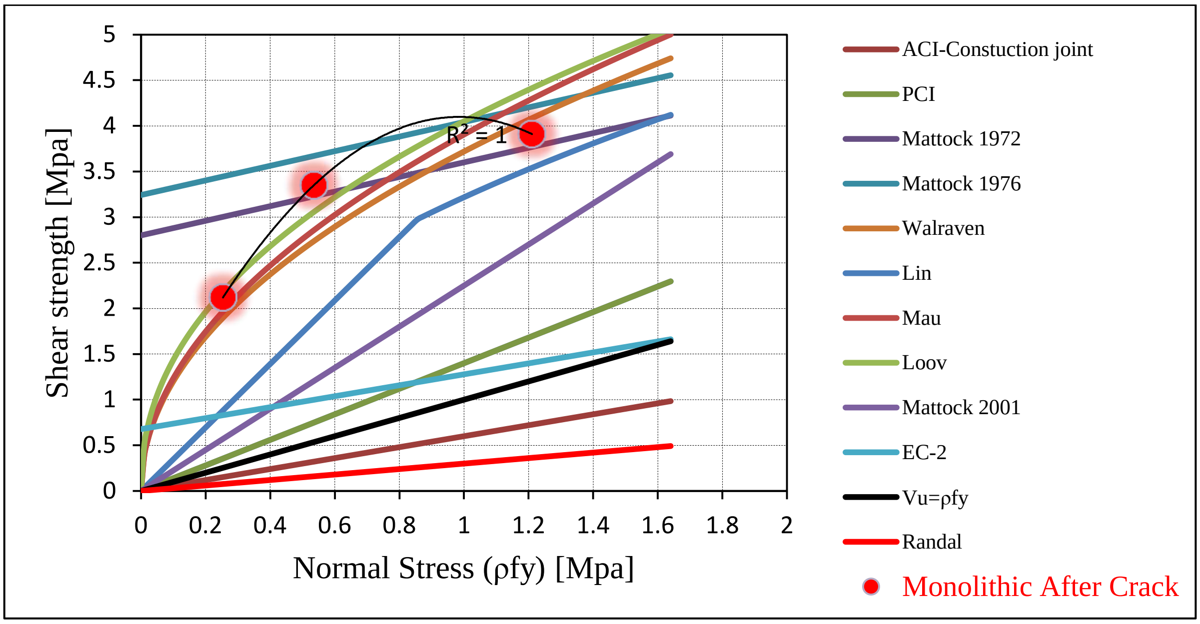


a). Monolithic Sample before cracking

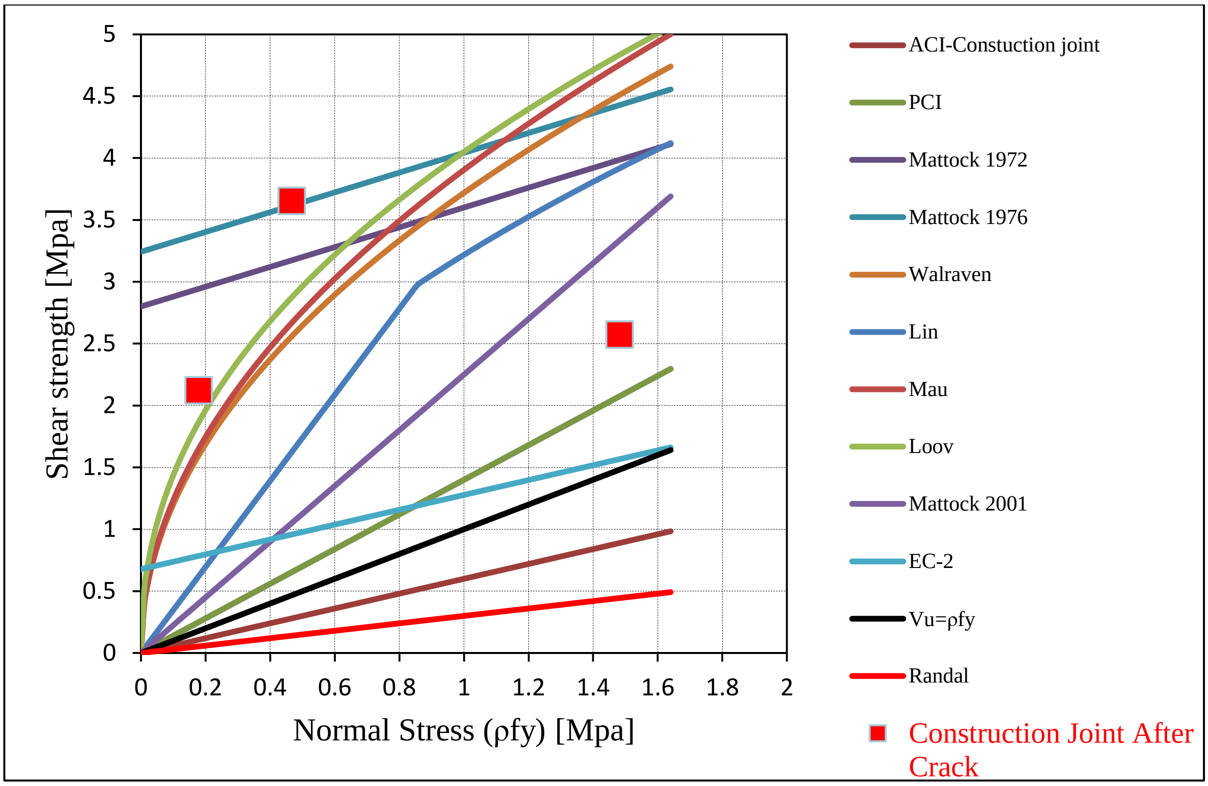


b). Sample with construction joint before cracking

Figure.5. 14: Comparison of experimental results with major models and codes before the formation of crack in the shear plane



a). Monolithic Sample after cracking



b). Sample with construction joint after cracking

Figure.5. 15: Comparison of experimental results with major models and codes after the formation of crack in the shear plane

SECTION 6. CONCLUSION AND RECOMMENDATIONS

6.1. Conclusion

Experimental investigation was carried to study the effects of construction joint in the interface shear transfer. The effects of construction joints were studied for different degrees of external bar restraints. In addition, different models proposed by researchers and building codes were compared with the experimental values.

The following conclusions are drawn from the experimental and theoretical evaluations:

- The presence of a construction joint would greatly affect the interface shear strength of reinforced concrete beams. Up to 35% reduction in strength is noted.
- The test results also show that the shear strength of both samples with and without construction joints increased as the area of steel crossing the shear plane is increased. The shear strength of the monolithic samples increased from 2.91MPa to 2.97MPa to 3.06MPa and the shear strength of samples with construction joint generally increase from 2.36MPa to 2.65MPa.
- We can also see from the test results that surface treatment could have a major effect in the interface shear strength. The test result shows that the shear strength for a construction joint with a smooth surface treatment is reduced from 2.91MPa to 1.91MPa (which is a 35% reduction).
- Building codes give a conservative estimate of the interface shear strength of reinforced concrete beams.
- The interface shear behavior before and after cracking is different and the test results show that the model by Mattock (Mattock,A,H, and Hawkins,N,M.,, 1972) is the best fit before the formation of crack and the model by Walraven (Walraven, 1980) is the best fit after the formation of crack.

In general, this work has shown that the presence of a construction joint affects the interface shear strength of reinforced concrete. As such the Ethiopian building code should pay a great deal of attention to the modeling of interface shear transfer.

6.2. Recommendation for future work

In addition to investigating the effects of construction joint in the interface shear transfer; this work identified numerous areas for future studies. Some of these ideas are listed below:

- This work focused mainly on investigating the effects of construction joint. The proper location of construction joint is not part of this work. Hence, a detailed study as to the proper location of construction joint could be beneficial.
- It should be highlighted that the values of shear strength given by design code expressions are significantly different from each other. Thus, further study could be beneficial in developing a model for the interface shear strength with construction joint to be used by our building code.
- In this work, the study concentrated only for smaller ratios of reinforcement bars crossing the shear plane. Similar studies with larger ratios will be important extensions of this work.
- This work focused mainly on medium strength concretes. Similar studies for high strength concretes could be beneficial in enriching the existing work.
- This work didn’t study the any of the measures that could be taken to moderate the reduction in interface shear strength caused by construction joints. Hence, a major study into how we can reduce the effect of construction joint could be vital.

Reference

ACI 224 Committee " Joints in Concrete Construction" ACI 224.37-95. - 1995.

ACI 318M-05 " Building code requirements for structural concrete and commentary," No.318-2005, Farmington Hills,MI 48333-9094, USA,471 p. - 2005.

Birkeland P.W, Birkeland H.W " Connections in Precast Concrete Construction,". - : Journal of the American Concrete Institute, 1966. - Vols. 63,No.3,PP. 345-368.

Bryan Barragan Ravindra Gettu, Luis Agullo, and Raul Zerbino Shear Failure of Steel Fiber-Reinforced Concrete Based on Push-Off Tests [Journal]. - [s.l.]: ACI Materials Journal, 2006. - Vols. V.103, No 4...

Eurocode 2 " Design of Concrete Structures-Part 1-1: General rules and rules for buildings," European Committee for Standardization, Avenue Marnix 17, B-1000 Brussels, Belgium,225p. - 2004.

Hofmeck, J.A.,Ibrahim,I.O. and Mattock,A.H., " Shear Transfer in Reinforced Concrete,". - : Journal of the American Concrete Institute, 1969. - Vols. 66,No.2,pp119-128.

Lin, I J and Chen, Y L " Shear transfer across a crack in reinforced high strength concrete." proc.,2nd East Asia-Pacific Conf.on Structural Engineering, and Construction, Chiang Mai, Thailand,85-91. - 1989.

Loov R E " Design of Precast Connections," paper presented at a seminar organized by Compa International Pte, Ltd.,Singapore. - 1978.

Loov, R and Patnaik, A; " Horizontal shear strength of composite concrete beams with rough interface." PCI J.39(1),48-67. - 1994.

Mast R.G., " Auxiliary Reinforcement in Concrete Connections," // Proceedings, ASCE,Vol.94,ST6,pp.1485-1504. - 1968.

Mattock A H " Shear transfer under monotonic loading across an interface between concrete cast at different times." Report SM 76-3, Dept. of Civil Engineering,Univ. of Washington,Seattle,Wash. - 1976.

Mattock A H " Shear-friction and high-strength concrete."ACI struct.J.,98(1),50-59. - 2001.

Mattock A H, Joha L, and Chow H C " Shear Transfer in Reinforced Concrete with Moment or Tension Acting Across the Shear Plane " [Journal]. -: Prestressed Concrete Institute. - No. 4: Vol. 20. - pp. 76-93.

Mattock A H, Li W K and Wang T C " Shear transfer in lightweight reinforced concrete " [Journal]. -: Prestressed Concrete Institute, 1976. - No. 1: Vol. 21. - pp. 20-39.

Mattock, A, H, and Hawkins,N,M., " Shear Transfer in Reinforced Concrete-Recent Research,". - : Journal of the Prestressed Concrete Institute, 1972. - Vols. 17,No.2,pp.55-75.

Mau, S T and Hsu, T T.C; " Discussion on Influence of concrete Strength and loading history on the shear friction capacity of concrete members." PCI J, PP 166-170. - 1988.

Norman.W.H "Precast-Prestressed Concrete Bridges," Part 2, " Horizontal Shear Connections,". - [s.l.]: Journal of the Research and Development Laboratories, Portland Cement Association, 1960. - Vols. 2,NO.2, pp38-58.

PCI Prestressed Concrete Institute PCI design handbook,4th Ed., PCI,Chicago. - 1992.

Randal N " Design recommendations for interface shear transfer in MC 2010 " [Journal]. -: Ernst & Sohn, 2013. - doi: 10.1002/suco.201300003...

Sagaseta J and Vollum R L " Influence of aggregate fracture on shear transfer through cracks in reinforced concrete " [Journal] // Magazine of Concrete Research. -: Institution of Civil Engineers, 2011. - Issue 2: Vol. 63. - pp. 119-137. - doi: 10.1680/macr.9.00191.

Santos M D " Assessment of the Shear Strength between Concrete Layers," Ph.D. thesis,University of Coimbra. - 2009.

Thomas T.c.Hsu, S.T. Mau, and Bin Chen Theory of shear Transfer Strength of Reinforced Concrete [Report]. - [s.l.]: ACO Structural Journal, 1987.

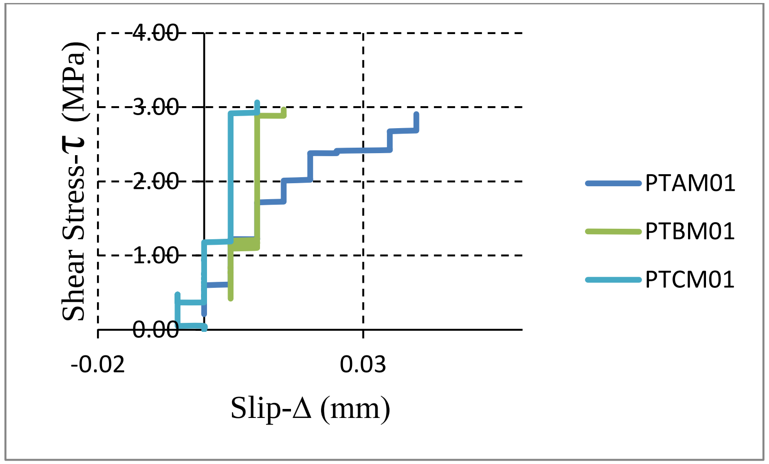
Walraven J C " Aggregate Interlock: A theoretical and experimental analysis " [Dissertations]. -: Delft University Press, 1980.

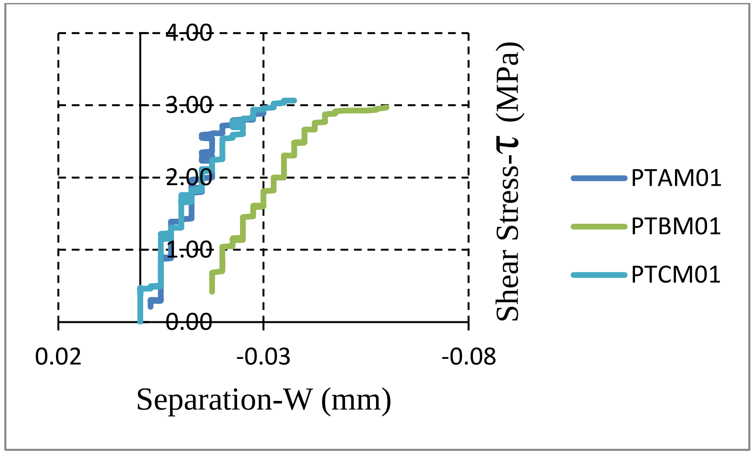
Walraven J.C.: "Experiments on shear transfer in cracks in concrete: Part II: Analysis of results". - Report No.5-79-10: Stevin Laboratory, Delft University of Technology, The Netherlands, 1997.

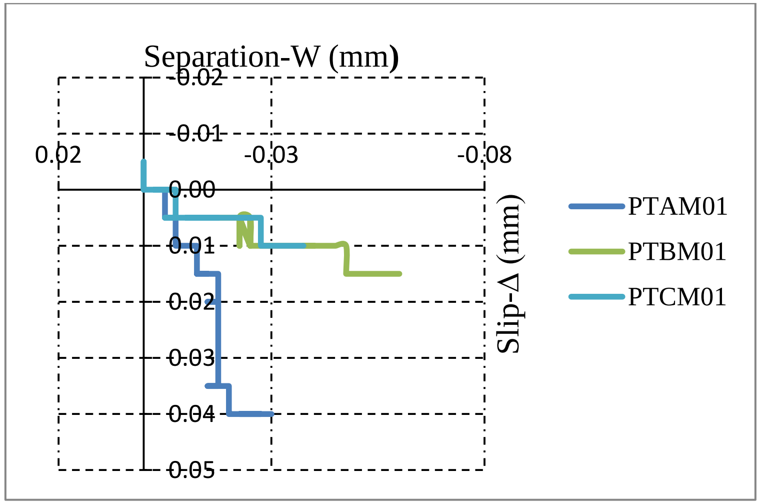
Walraven, J.C., Vos.E,Reingardi.H.W.: " Experiments on shear transfer in cracks in concrete. Part I: Description of results ". - Netherlands: Stevin Laboratory, Delft University of Technology, 1979. - Vols. 5-79-10.

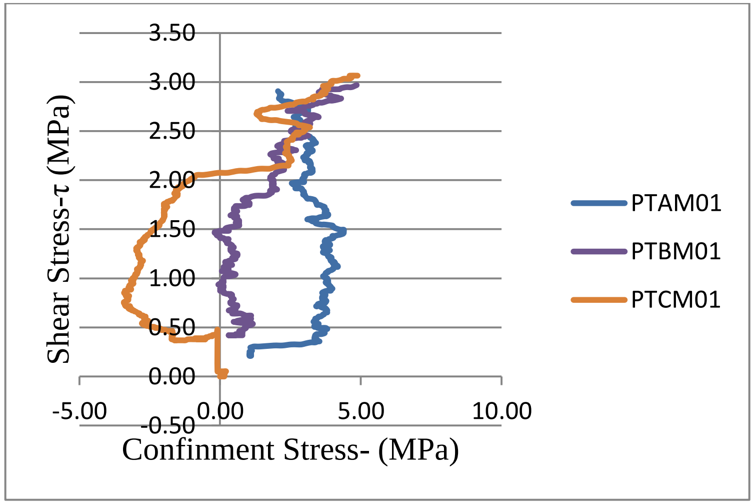
Walraven.J.C.; Frenay. J.;Pruilssers.A.; " Influence of Concrete Strength and Load History on the Shear Friction Capacity of Concrete Members,". - : Journal of the Prestressed Concrete Institute, 1976. - Vols. 21,No.1,pp.20-39..

Annex 1 (Summary of Test Data for Monolithic Samples before Crack)

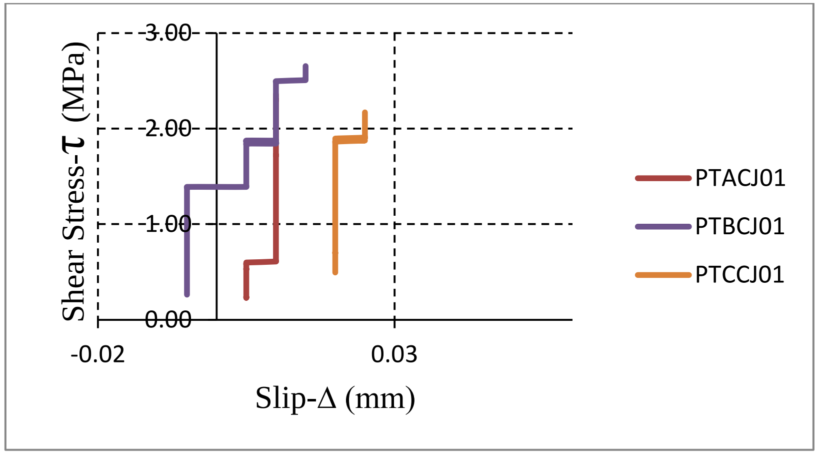


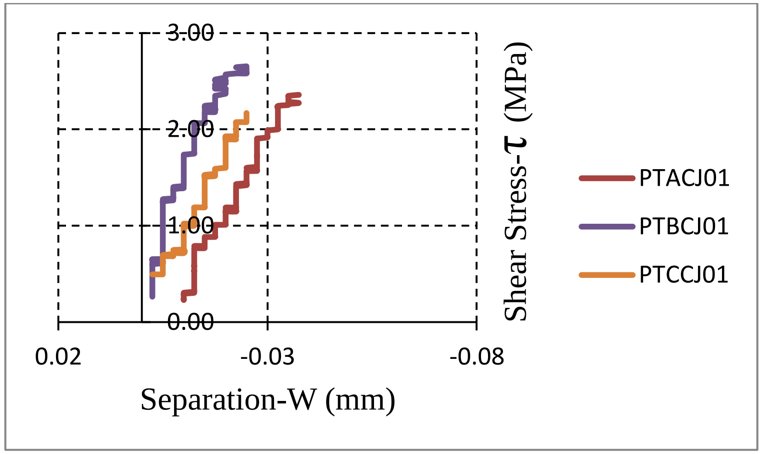


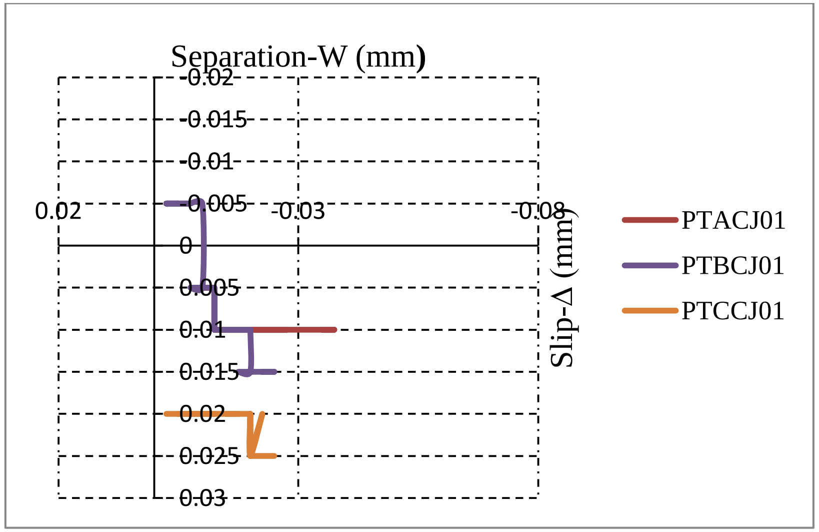


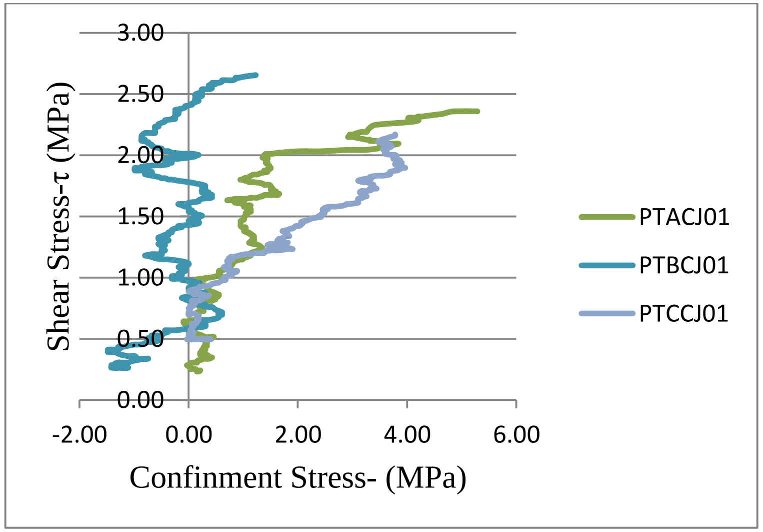


Annex 2 (Summary of Test Data for Samples with Construction Joint before Crack)

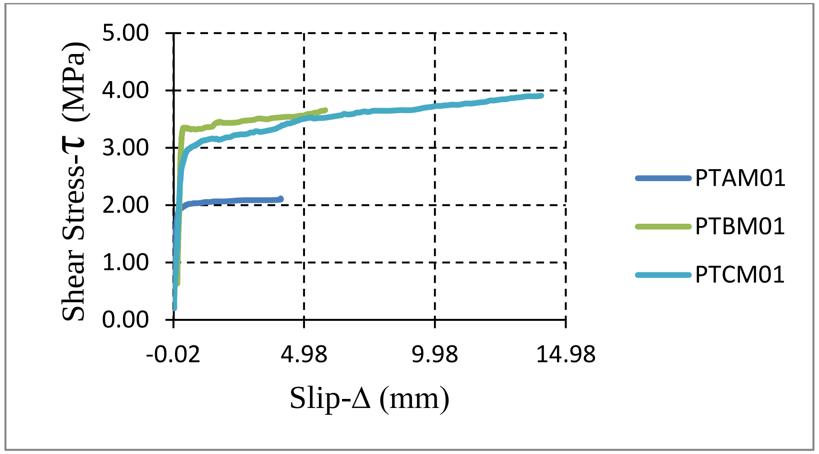


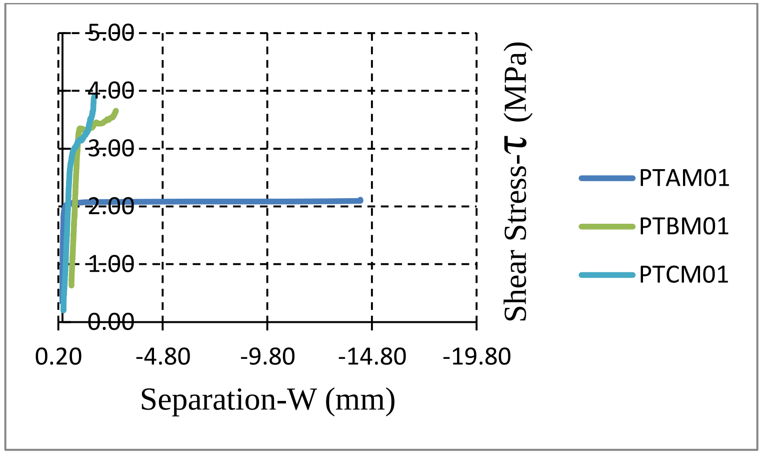


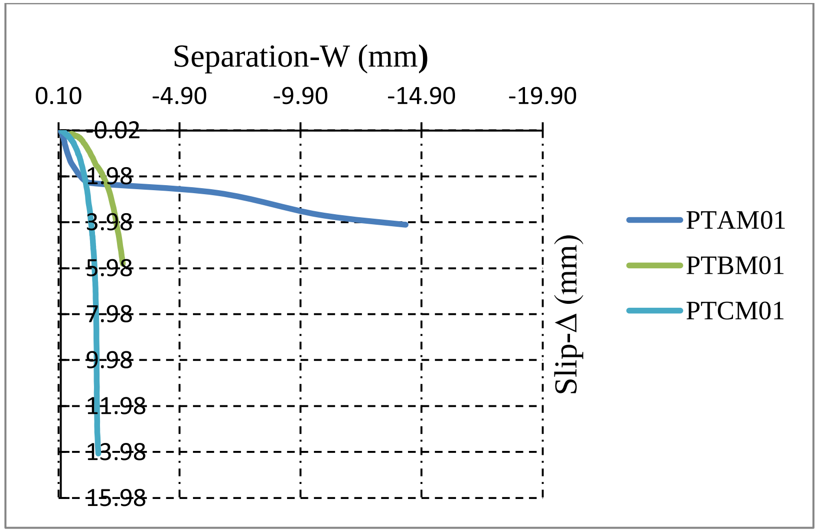


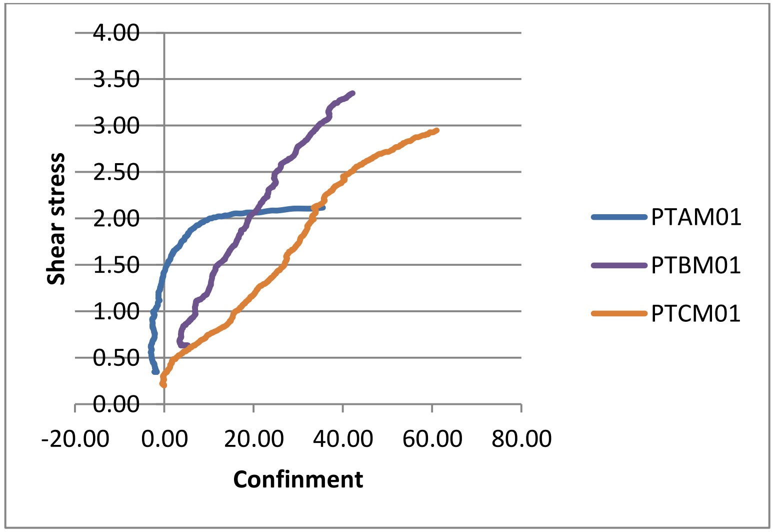


Annex 3 (Summary of Test Data for Monolithic Samples after Crack)

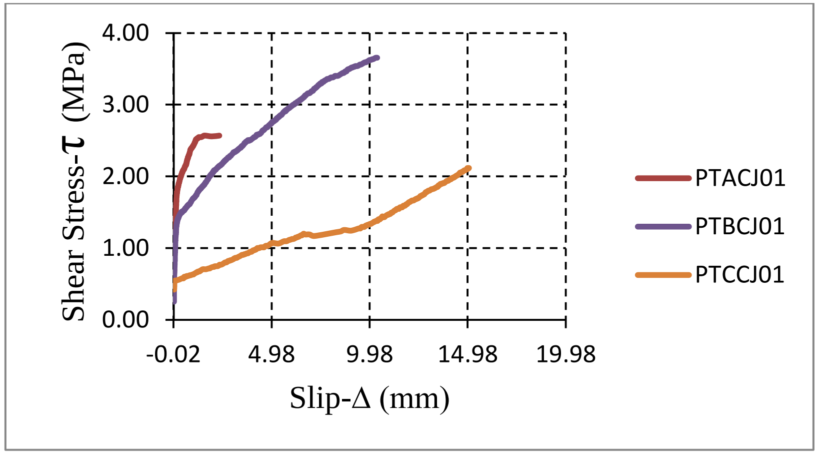


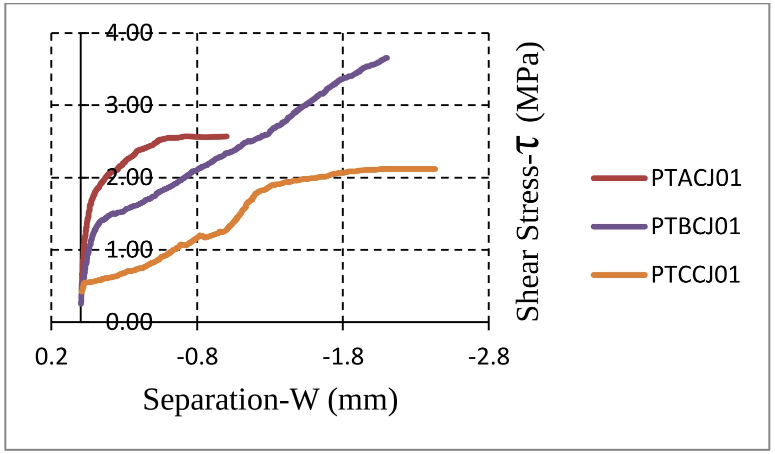


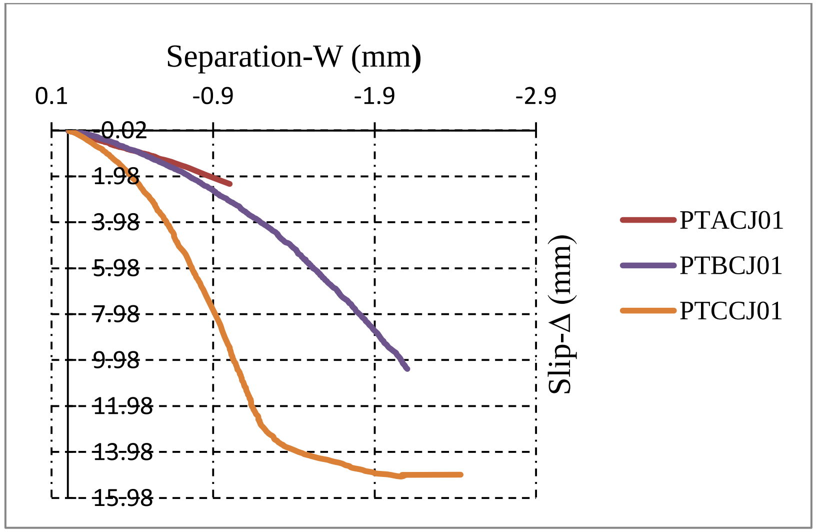


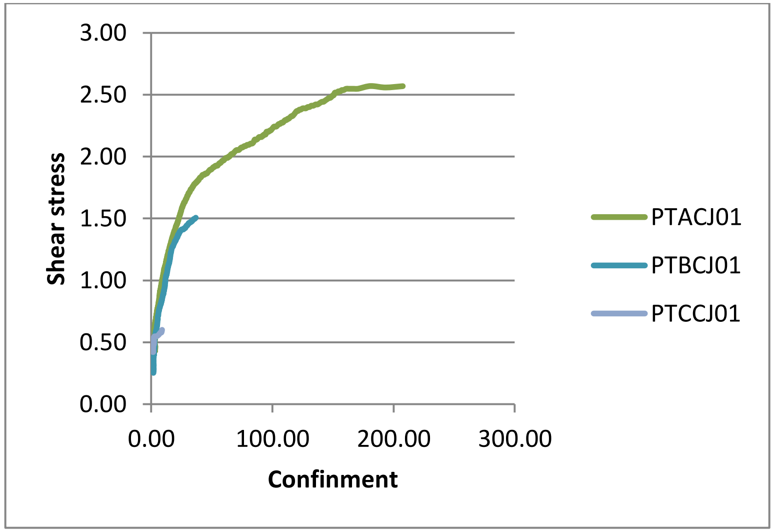


Annex 4 (Summary of Test Data for Samples with Construction Joint after Crack)









Annex 5 (Formwork Detail)