

ADDIS ABABA UNIVERSITY  
ADDIS ABABA INSTITUTE OF TECHNOLOGY  
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING



SHEAR STRENGTHENING OF SHEAR CRITICAL REINFORCED CONCRETE BEAMS

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**A Thesis in Structural Engineering**

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ADDIS ABABA UNIVERSITY  
ADDIS ABABA INSTITUTE OF TECHNOLOGY  
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“SHEAR STRENGTHENING OF SHEAR CRITICAL REINFORCED CONCRETE  
BEAMS”

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**ABSTRACT**

Upgrading of existing structures becomes necessity due to various reasons; some of those are revised design code and deterioration with time due to environmental effects. Design codes are constantly being revised in many countries including Ethiopia as new loading requirement dictates for higher strengths demanded of structural members like shear, flexure, axial and torsion. This study focuses on the shear capacity assessment and strengthening of shear critical RC beams. In this research eight RC beams were investigated. All beams have the same geometric dimensions and reinforcement ratio ( $a/d=3.11$ ,  $\rho=0.01314$ ). The beams were intentionally designed to fail in shear and different types of shear strengthening was implemented for each RC beam by varying the configuration of the stirrups used for shear strengthening. The amount of shear reinforcement utilized for strengthening was kept constant. All the strengthening methods were found to enhance the shear strength of the control RC beams, with varying degree of efficiency. However, a beam strengthen with vertical leg stirrups inserted by drilled along depth of beam and confined using horizontal legs with parallel vertical legs configurations (beam type-3) were found to be the most effective type. Analytical simulation were done using a non-linear 3D finite element formwork using fixed-four way crack model where the path and time dependent constitutive laws for tension, shear and compression are rooted in (DUCOM-COM3D). The simulation result were found to reproduce the experimental results reasonably, verifying the reliability of the mode failure as well.

**Key words:** RC beam, shear, strengthening, vertical legs, confinement

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## CHAPTER-1. INTRODUCTION

### 1.1 Background

Upgrading of existing structures has emerged as one of the major construction activities all over the world today. Upgrading of existing structures becomes necessity due to various reasons; some of those are reversed design code and deterioration with time due to environmental effects. Design codes are constantly being upgraded in many countries including Ethiopia as new loading requirement dictates for higher strengths demanded of structural members. Numerous concrete structures constructed in the past in countries like USA and Japan do not meet current seismic design codes especially concerning shear capacity and ductility. For example, the Hyogoken–Nanbu Earthquake in 1995 caused tremendous damage to concrete structures in Japan. (Hiroshi M. & Bimal Babu A., 2005) Several reinforced concrete piers and rigid frames, used for elevated highways were severely damaged during this earthquake. The failure pattern showed insufficient shear capacity and lack of ductility in piers and main beams of these structures. Many elevated highways constructed in Japan have been built according to the Design Specifications issued before 1980, which do not fully address these issues.

The situation in Ethiopia is quiet similar, and most of the existing buildings in Ethiopia were designed based on the provisions of EBCS-1995 codes. In the Ethiopia context based on the research carried out the department of geophysics, the expected ground acceleration has increased and new design codes have been released as of 2015. Recently, the design code was revised for higher strengths demanded of structural members. In most areas or zones the bed rock acceleration has been increased to double in the recently design code. For example an existing G+7 condominium building located in Addis Ababa was checked; and the shear demand will increase up to 97% if analyzed using the provisions of the new code. This load increment has put the safety and integrity of several existing building structures in a question. Therefore, the researcher want to enhance their strength before destruction of life and goods. And also to protect structures from sudden failure (shear failure). Strengthening of those structures would be desirable if speedy, economic, effective, and simple strengthening techniques were available.

There have been a number of studies in the past on shear strengthening of reinforced concrete beams using different techniques, such as steel plates and brackets bonded on

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beam web, near-surface mounted fiber-reinforced polymer (FRP) rods, externally anchored stirrups and carbon fiber reinforced polymer (CFRP) sheets materials. Most of the studies use expensive materials for shear strengthening but those methods are not feasible in terms of economic aspect. But the current research was focused on adding of stirrups externally and internally using different techniques and configuration types which are practicable. In this study intentionally a very small pre-strain (initial strain) was applied to vertical shear stirrups.

For reinforced concrete beams, externally anchored stirrups were found very effective method of shear strengthen than other methods like steel brackets, steel plates and vertical strips with plate. (Hiroshi M. & Bimal Babu A., 2005) But this study does not compare or relate the additional stirrups provided used for shear strengthening of existing beams with the conventional web reinforcement design which provided before casting. Comparison of those two, makes easily applicable additional web reinforcement of shear strengthening in practical usage. In addition to this, the previous study does not concern about the aesthetic value of the structure. Because the externally anchored stirrups provided increases the beams thickness and also affect the architectural views. In the previous study, the researcher does not recommend possible ways of strengthen techniques for areas where there are architectural and specification detailing (structural detailing) restriction occurs. The current research answer all those limitations and used easily available material to be cost effective.

In this research a total of eight RC beams were used to investigate the shear strengthening of beams using various techniques. All beams are without internal web reinforcement and have the same geometric parameters and steel ratio. All beams have 3.11 ratio of shear span to effective depth. All beams were cast at laboratory conditions and the concrete cylinder compressive strength was tested at 28 days. The controlled variables of this experimental research were quality of ingredients (cement, sand, aggregate, water and reinforcement), amount of water for curing, water to cement ratio and dimensions of beams. The effect of mixing was avoided as much as possible by using the same mixing and placing time.

Two of them were control beams (Beam type-1) and this beam type was used as a reference for different strengthening techniques of beam. But the rest beams are strengthen with different techniques and configuration type of web reinforcement along critical shear span.

All beam are intentionally designed to fail in shear. This research gives relationship between the conventional web reinforcement design and the additional shear reinforcement provided for shear strengthening. Beam type-2 was strengthened with external stirrups provide along the shear span and has two number of samples. Beam type-3 was strengthened by inserted vertical leg along the drilled depth of beam and connect the vertical leg stirrups with horizontal plates using bolting at both ends. In this beam type the vertical stirrups provided were parallel in configurations. In beam type-4 and beam type -5 horizontal plates were not provided unlike that of beam type-3. Beam type-4 and beam type-5 were strengthened by inserted vertical legs along drilled depth of beam with parallel and staggered configurations of holes respectively. The sixth type of beam were strengthened by inserting stirrups in the grooved section. The concrete cover of a beam was grooved to provide the shear stirrups along shear span. In all beams, grooved and drilled parts of the beams were filled by cement-based mortar.

All beam types was tested in the same manner. And data's are recorded to draw the load-deflection curves and load- strain curves. These beams was used to know the increment of shear capacity due to different configurations of shear stirrups provided on reinforce concrete beams.

Furthermore, numerical analysis based on a non-linear FEM was also performed to simulate the behavior of these beams, and the applicability of FEM to these shear strengthened beams was confirmed.

## **1.2 Objective**

This study was aimed to assess the relative shear strengthening performance of existing shear critical slender RC beams using different methods and configurations of shear stirrups provided along the shear span. Furthermore the study aims to make relationship between the providing shear stirrups for retrofitting of increase in shear obtained on existing RC beams and the conventionally provided internal shear reinforcement during initial casting.

### **1.3 Scope of the Study**

This research will include only normal slender beams with internal force of flexure and shear. Deep beams, beam-columns, Pre-stressed beams and beams made of high-strength concrete will not be covered in this document.

### **1.4 Significance of the Study**

The Ethiopian building code standard has been revised after two decades. The new design code has emerged with increased peak ground acceleration passing. And the existing structures are inadequate due to the increment of in peak ground acceleration. So our society always call to researchers to give a good and effective solutions of rehabilitation inadequate existing structures in shear capacity. This study provides an effective solution to risk associated with brittle failure of existing structures which is an urgent issue and a great concern of our society about the safety of the existing infrastructures particularly buildings. In response, researchers are expected to provide effective solutions on the rehabilitation of inadequate existing structures.

### **1.5 Methodology**

The overall process of this research includes literature review, examination of building design codes, experimental program and analytical simulation using non-linear finite element modeling.

First the researcher studied the difference of both old and revised design code parameters. Then a building was analyzed under the old and revised design code parameters using analytical software to check if their output result will be different in design shear values.

Different types of technique were reviewed to select the economic and effective way of strengthening method. In this study, additional of shear reinforcement were used to strengthen the slender beam in shear capacity. These additional shear stirrups were provided along shear span of a beam in different type of techniques and configurations.

Finally, finite element analysis was performed for these different configuration and technique types of additional web reinforcements. The reliability of software simulated result obtained was verified with the experimental results.

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## **CHAPTER-2. LITERATURE REVIEW**

### **2.1 Strengthening of Structures**

Upgrading of existing infrastructures has emerged as one of the major construction activities all over the world today. Upgrading of existing structures becomes necessity due to various reasons; some of those are revised design code and deterioration with time due to environmental effects. The existing concrete structures have require strengthening or stiffening in order to increase their ultimate flexural or shear capacity, or to control deflections and cracking. Richard Andrew B. & Geoffrey Charles M. (2005) Design codes are constantly being upgraded in many countries as new loading requirement dictates for higher strengths demanded of structural members. Numerous concrete structures constructed in the past in countries like USA and Japan do not meet current seismic design codes especially concerning shear capacity and ductility. The Hyogoken–Nanbu Earthquake in 1995 caused tremendous damage to concrete structures in Japan. Several reinforced concrete piers and rigid frames, used for elevated highways were severely damaged during this earthquake. The failure pattern showed insufficient shear capacity and lack of ductility in piers and main beams of these structures. (Hiroshi M. & Bimal Babu A., 2005)

Similarly, in Ethiopia a new design code has been released. This revision of code was done for the higher strength demand of structures. Earth quake parameters and empirical formulas of shear resistance were changed in the revised code.

### **2.2 Strengthening for Shear**

Reinforced concrete structures are designed to fail by flexure and also the amount of flexural reinforcement have limits to ensure ductile failure and give warning for occupant. But shear failure is sudden and brittle. Generally in the design of RC beams, this failure type should be avoided. Therefore, existing structures should be highly checked for their shear strength capacity. Design codes have been continually improved but structural failures have result from inadequacies in design for shear. (Richard Andrew B. & Geoffrey Charles M., 2005)

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It is accepted, however, that in a reinforced concrete beam the shear force is carried by a combination of: concrete in the compression zone; aggregate interlock; dowel action and shear reinforcement (if provided). The factors that affect the shear strength of a reinforced concrete beam are: concrete properties; beam size; beam shape and reinforcement details. There are three basic shear failure types, dependent upon shear span to depth ratio can be categorized as: deep beam failure; shear compression and diagonal tension.

In Ethiopia, the shear empirical formulas of shear resistance were changed in the revised design code. Generally, both the empirical formulas of shear resistance concrete and web reinforcement in these old and revised design codes were different. The variation of both design codes in shear resistance concrete was depending mainly on compressive strength concrete. Specifically for this study, the cylinder compressive strength at tested day was vary from 23 to 36 MPa. For 23 MPa of compressive strength the old code had 11.77% less in shear resistance of concrete than the revised code. But for 36 MPa of compressive strength the old code had 2.39% higher in shear resistance of concrete than the revised code. Generally for normal concrete grade, the old design code is lesser in shear resistance capacity than the revised design code. However, in shear resistance of web reinforcement the old design code has 10% greater than the revised design code. Generally, both codes have a variation in their empirical result values. But to compare relatively it depends on the amount shear resistance of concrete and web reinforcement. Therefore, structures needs strengthening in shear due to changing empirical formulas in addition to the earthquake effect.

Shear can be critical for some existing structures, designed with old shear provisions, presenting low quantities of transversal reinforcement or exposed to important shear loadings. The deficiency of shear strength may lead to a brittle collapse. Various aspects, such as the resistance mechanism of the strengthened element, the distribution of resisted shear force between original and strengthening materials, the bonding mechanism and the overall efficiency of a strengthening solution have motivated many experimental research works involving different strengthening materials and techniques.

Different techniques like steel brackets, steel plates, vertical strips and externally anchored stirrups were used to enhance the shear capacity of inadequate existing reinforced concrete beams. All techniques were found effective in enhancing the shear strength of reinforced concrete beams but externally anchored stirrups were found very effective than the other

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methods. (Hiroshi M. & Bimal Babu A., 2005) The previous study gives an important clue to researchers. But the previous study does not relate the additional shear stirrups provided for strengthening with the conventional web reinforcement design. Beam type-2 of the current research is somewhat similar in methodology with previous study. Using the previous study, the current researcher wants to relate the retrofitting stirrups provided along the shear span for shear strengthening with the conventional shear reinforcement design. The additional shear stirrups provided for shear strengthening make relate with conventional shear reinforcement design was used to practice other spacing type of shear stirrups in practical work easily.

Near-surface mounted (NSM) fiber-reinforced polymer (FRP) rods is a promising technology for increasing flexural and shear strength of deficient reinforced concrete (RC) members. (Laura De L. and Antonio N.2001) They used a Carbon FRP deformed rods for shear strengthening and the study were focused on spacing of the rods, strengthening pattern, end anchorage of the rods, and presence of internal steel shear reinforcement. The study was somewhat similar in method of strengthened with the current research of Beam Type-6 but this previous study does not deals with mechanics. In previous study the role of confinement is not discussed. The current research gives a solutions of those previous research limitations.

There was no internationally or locally research paper works related to the shear strengthening techniques used in Beam Type-3, Beam Type-4 and Beam Type-5. So, these technique types were a new work in shear enhancement of inadequate existing RC elements.

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## CHAPTER-3. EXPERIMENTAL PROGRAM

### 3.1 Experimental Strengthening Techniques

In this experimental program, specimens were intentionally categorized into three main groups based on their functions, shear stirrup configurations, architectural and design specifications (structural detailing) requirements. All beams were casted with the same specifications. But after, these beams were made some modifications to strengthening in shear resistance excluding control beams.

Control beams were used as a base mark to compare those strengthened beams. Control beam was represent by beam type-1 and this beam type was not modified.

Secondly, it is better to strengthen existing beams without losses its architectural beauty and increase its cross section. Simply inserting vertical shear stirrups internally by drilling the concrete core. This method was not affect its architectural appearance and cross section of the existing beams. A good example of this method of strengthen was Beam type-4, which was provided only vertical shear stirrups along shear span with parallel in configuration type. But to compare the effectiveness of this beam type depending on configuration of shear stirrups only, beam type-5 was proposed with staggered in configuration type. These both beam types were without horizontal legs but horizontal legs has a great role in confinement of concrete and in resistance of torsion. Thus to have effective strengthen technique for beams where subjected to torsion and needs a confinement of concrete, beam type-3 was proposed with horizontal legs. All these beams were used when the design detailing (structural detailing) have enough spacing between longitudinal bars and it's suitable for drilling. But if it is not sure about detailing or not suitable for drilling, beam type-6 was a good strengthening method and in this beam type the shear stirrups was provided by grooving the concrete cover of the beam.

In Beams where no option to strengthen their shear capacity without increase cross section and change its architectural beauty, beam type-2 was the only option method of strengthen. In this beam type shear stirrups were provided externally and consists of both legs. After the shear stirrups were tied on the shear span of existing beam, finally the beam was plastered to cover the external provide shear stirrups.

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## 3.2 Experimental Strategy

Shear strengthening of beams were done by providing additional shear stirrups along the shear span of a beam using different configuration types. A total of eight beams were tested in this experimental research. All the beams have the same dimensions and reinforcement details. The beam has a width of 200 mm, depth of 250 mm and overall length of 1700 mm. The beams were reinforced and detailed as shown in **figure 3.1**. Beams were designed intentionally to fail in shear. In all beams there were no shear reinforcement internally. However, stirrups were provided outside the shear spans to mount the longitudinal reinforcement and to prevent the beam from anchorage failure (bond failure). The average cylinder compressive strength of concrete used was range 19-30 MPa at 28 days. The average yield strength and elastic modulus of longitudinal reinforcement were range 523-655 MPa and 200 GPa respectively. Deformed bar diameter of 8mm and plate (30 mm width, 8mm thickness) were used for vertical and horizontal stirrups respectively in this program with some modifications. Control beam was used as a baseline to evaluate and compare the strengthen beam types. Specimen detail are described in **figure 3.1 and table 3.1**.

Over the eight beams the two beams were control beam (Beam Type-1) which was not strengthen in shear capacity. Beam Type -2 was strengthened, it was just tied with 130 mm spacing web reinforcement externally without core concrete modification, by provide external shear stirrups along the shear span and have two beam samples. The third type was first made a modification to have a hole of 10mm in diameter along the depth of beam every 130mm spacing in parallel configurations. Then this beam type was strengthened by inserting vertical leg shear stirrups along the drilled depth of beam and tied with horizontal legs using bolting in both sides as shown in **figure 3.2 (c)**. The fourth beam type was the same as Beam Type-3 in all procedure but the only difference was the absence of horizontal leg shear stirrups on this beam type. In this beam type, ends of vertical leg stirrups were tied with bolt to protect the stirrups from slip. Beam Type-5 was made the same modification as Beam Type-4 but the holes configuration ware staggered. This beam type was strengthened the same as Beam Type- 4 as shown in **figure 3.2 (e)**. In sixth beam type, concrete cover was grooved in all sides' perpendicular to longitudinal axis. This beam was strengthened by providing the shear stirrups along the grooved section. All

grooved and drilled of beams were filled by cement-based bonding material as shown in **figure 3.2 (f)**.

Diameter of 8 mm deformed bar was used as a vertical leg shear stirrups. To brace both legs, this deformed bar was made a thread of 6 mm in both ends of vertical leg to tie with the horizontal leg using bolts.

All beams have the same longitudinal reinforcements, internal shear reinforcement were provided out of the shear span at both ends. Beams were reinforced with two deformed bars of 10 mm diameter ( $\text{Ø}10$ ) and 20 mm diameter ( $\text{Ø}20$ ) in compression and tension zone respectively. All reinforcement bars were anchored enough development length to prevent bond failure. Beams were designed to have a flexural to shear strength ratio of 0.53, the purpose of these type of beams were to devise shear strengthening techniques. Finally the strengthened beams were intentionally design to fail in shear.

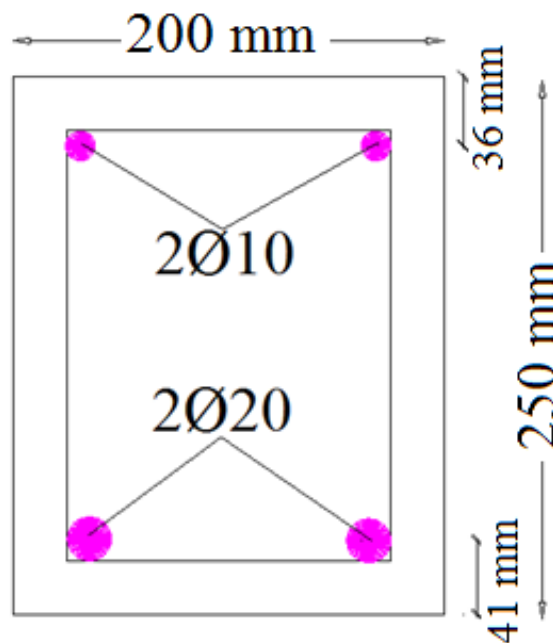
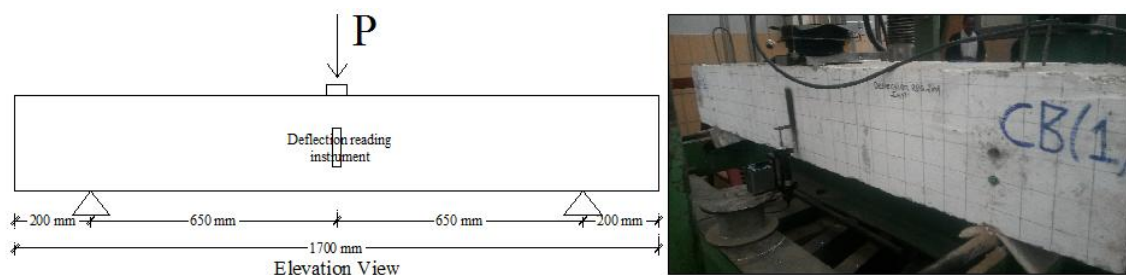


Figure 3.1: **Cross Section and Reinforcement Detail of All Beams**

a) Beam Type-1



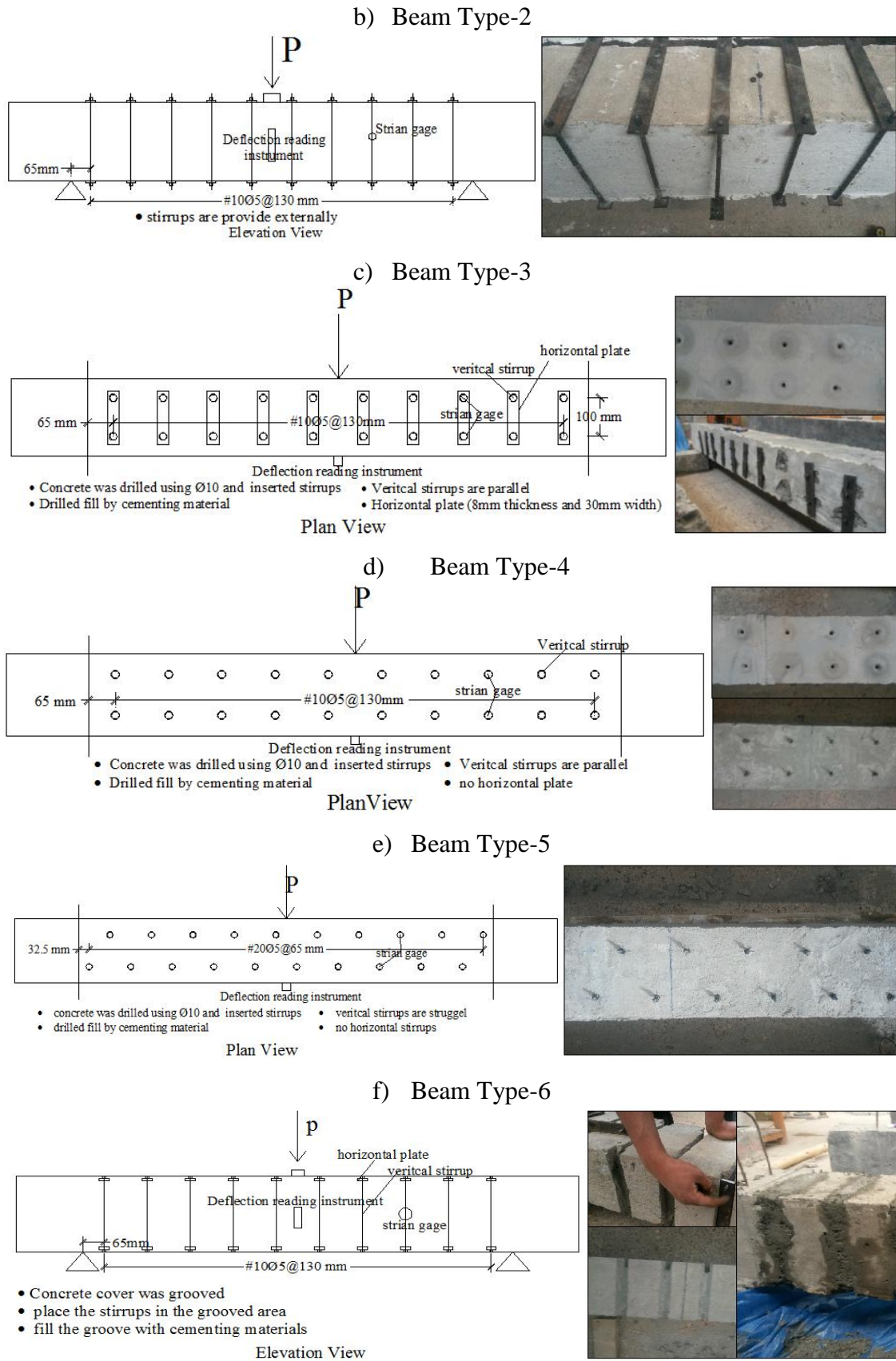


Figure 3.2: Beam Types and Configuration of Web Reinforcement

1

Table 3.1: Specimen's detail

Beam code	Description of beam and placement of additional web reinforcement	No- of sample	Spacing of additional vertical stirrups (mm)	Length of vertical leg stirrups (deformed bar Ø8) (mm)	Length of horizontal leg stirrups (plate 30x8mm) (mm)
Beam type -1	Control beam	2	-	-	-
Beam type -2	Stirrups provide externally	2	Ø5c/c130	310	245
Beam type -3	Stirrups inserted internally( by drilling) but vertical legs are parallel and tie with horizontal legs	1	Ø5c/c130	300	-
Beam type -4	Stirrups inserted internally( by drilling) with parallel vertical legs and no horizontal legs	1	Ø5c/c130	300	-
Beam type -5	Stirrups provide internally( by drilling) with struggle vertical legs and no horizontal legs	1	Ø5c/c130	300	149
Beam type -6	Stirrups provide in concrete cover (by grooving)	1	Ø5c/c130	250	190

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### 3.3 Materials

Beams casted in this experimental research were made up of steel and concrete materials. Deformed bars and flat plates were materials used as vertical and horizontal shear stirrups respectively for shear strengthening of beam in this study. Those material are quantified their strength and mechanical properties was discussed as below.

#### 3.3.1 Concrete

All necessary data's used for mix design are determined in laboratory room. Concrete was proportioned and mixed according the ACI mixing design. All beams were casted by steel molds and six cubes are casted to represent a compressive strength of a beam. Three of those cubes are tested at 28 day and their average compressive strength was taken. The other left three cubes were tested at testing day of the beam, those cubes was used to factor the compressive strength of 28 days. The cube was 150x150x150 mm in dimension. Due to shortage of materials two samples were used to cast the beams but their mix design was identical.

Table 3.2: Material properties

Material properties	Sample-1	Sample-2
Max. aggregate size (mm)	25	37.5
Specific gravity of cement (Cement; type 1)	3.15	3.15
specific gravity of sand	2.51	2.55
Fineness modulus of sand	2.60	3.00
Absorption capacity of sand (%)	2.11	2.25
Moisture content of sand (%)	2.05	4.57
specific gravity of Coarse aggregate	2.61	2.76
Compacted unit weight of Coarse aggregate (KN/m <sup>3</sup> )	1558.3	1630.2
Absorption capacity of Coarse aggregate (%)	2.46	1.16
Moisture content of Coarse aggregate (%)	2.81	1.84
Water to cement ratio	0.62	0.62

Table 3.3: Mix proportion

Material	Sample -1		Sample -2	
	Quantity	Ratio	Quantity	Ratio
	(kg/m <sup>3</sup> )		(kg/m <sup>3</sup> )	
Cement content	314.52	1	287.65	1
Fine aggregate content	812.46	2.58	855.78	2.98
Coarse aggregate content	1097.29	3.49	1148.83	3.99
water content	192.84	0.61	151.72	0.53

Table 3.4: Cylinder Compressive Strength at 28 day and at tested day

Type of Beam	Average Compressive stress at 28 day (MPa)	At Test day		Type of sample
		Average Compressive stress(MPa)	Testing date (day)	
Beam Type-1(1)	26.08	34.1	52	Sample-2
Beam Type-1(2)	22.1	26.66	56	Sample-1
Beam Type-2(1)	19.29	23.89	58	Sample-1
Beam Type-2(2)	23.28	28.35	52	Sample-1
Beam Type-3	29.44	35.38	57	Sample-2
Beam Type-4	24.69	27.7	57	Sample-1
Beam Type-5	27.02	33.68	56	Sample-2
Beam Type-6	21.39	25.59	62	Sample-2



a) Silt content of sand



b) Quartering of aggregate

Figure 3.3: **Materials and Concrete Mix**

### 3.3.2 Reinforcement bar

Concrete is weak in tensile strength, instead steel was used in the tension zone due to its higher tensile strength properties. Those steel was fabricated in factory but it needs to check the current strength in laboratory. All steel material (deformed bar and flat plate) are grade 60 made in Turk and those material are checked their current strength at laboratory. Deformed bar diameter of 10mm and 20mm were used in the compression and tension zone of concrete beam respectively. Deformed bar diameter of 8 mm was used for Vertical stirrups with some modification on both ends. Flat plate was used as horizontal leg of shear stirrups with some modification. The ends of vertical stirrups was made to have a threaded 6 mm diameter, these thread used to have a bond between horizontal and vertical legs using bolts.

Table 3.5: Tensile Strength of Longitudinal Reinforcement

Specimen No	Actual		Yield stress (MPa)	Failure Load (kN)	Failure stress (MPa)	Elongation (%)
	Diameter(mm)	Yield Load (kN)				
1	9.46	36.80	523.57	44.30	630.28	9.50
2	9.42	38.70	555.29	52.00	746.13	11.00
3	18.77	180.20	651.23	211.5	764.35	12.50
4	18.86	178.90	640.38	217.20	777.48	12.00
5	18.69	179.50	654.27	214.20	780.75	11.50

Table 3.6: Tensile Strength of Vertical Leg Stirrups

Specimen No	Diameter (mm)	Yield Load (kN)	Yield	Failure	Failure stress (MPa)	Elongation (%)
			stress (MPa)	Load (kN)		
1	5	12.70	646.81	15.22	775.15	12.5
2	5	10.90	555.13	13.10	667.52	10.3
3	5	11.00	560.22	13.30	677.71	11.5

This table shows deformed bar Ø8 was modified to have Ø5 in mechanical laboratory.

Table 3.7: Tensile Strength of Horizontal Leg Stirrups

Specimen No	Width (mm)	Effective width (mm)	Thickness (mm)	Net area (mm <sup>2</sup> )	Yield	Yield	Failure	Failure	Lengt h (mm)	Lu (mm)
					Load (kN)	stress (MPa)	Load (kN)	stress (MPa)		
1	30.00	22.00	8.00	176.00	82.99	471.53	88.06	500.34	50.00	56.50
2	30.00	22.00	8.00	176.00	81.61	463.69	87.25	495.74	50.00	56.00
3	30.00	22.00	8.00	176.00	81.68	464.09	87.06	494.66	50.00	56.00
Average					82.09	466.43	87.46	496.91	-	56.17



a) Tensile strength machine



b) Tensile strength of horizontal plate stirrups



c) Tensile strength of vertical stirrups



d) Bolt bond and bearing capacity

Figure 3.4: Tensile Capacity of Steel and Connections

### 3.4 Procedure and Specimens Fabrication

All parameters used for mix were calculated in laboratory using their specific procedure manual. And all need materials like coarse aggregate, fine aggregate and cement (OPC)

were prepared. Gradation and all need parameters were determined at laboratory for both aggregates. Analysis of mix design was done using ACI code. Mixing was done by machine and to produce C-25 MPa compressive strength of concrete cube test at 28 days. The effect of mixing was avoided as much as possible by using the same mixing and placing time. Dry mix of ingredient (coarse aggregate, sand and cement) was done for one and half minute. Then wet mix was done for one minute using fresh water.

Longitudinal reinforcement was provided according the analyzed area of reinforcement. According to the design the anchored development length was provided to avoid the bond failure of a beam.



Figure 3.5: **Reinforcement's Detail**

Formwork was prepared with specific dimension of beam, and concrete was casted on the formwork. All beams were casted at laboratory room to avoid the temperature effect, normal curing was done for 28 days. After the concrete was set, the formwork was removed. Struke off formwork were done after 24 hours of concrete casting. And then beams were started to cure a fresh water.



a) Preparation of formwork



b) Slump test



c) Casted concrete



d) Removed formwork



e) Concrete in curing

**Figure 3.6: Preparation of Formwork, Slump Test, Casting and Curing of Concrete**

At 28 days three cubes per beam were tested to measure the respective compressive strengths of a beam, and categorizing of the beam was done depending on web reinforcement configurations to flow their specific procedure of modifications. Depending on their configurations the beams were grooved and drilled.



**Figure 3.7: Cubes Weighted for Test Compressive Strength**



a) Specimen drilling



b) Specimen grooving

**Figure 3.8: Drilling and Grooving of Specimens**

Shear stirrups was placed or provided on drilled and grooved sections and then fill with normal cementing materials. Curing was done for the filled cementing material. Finally, the specimens were made ready for test.



Figure 3.9: Drilled and Grooved Wash from Dust



Figure 3.10: Stirrups Placed on the Drilled and Grooved



Figure 3.11: Fill the Drilled and Grooved after Placing the Stirrups



a) curing

b) make ready the specimen for test

Figure 3.12: Curing and Ready the Specimen for Test

### 3.5 Loading Setup

The beam was placed on steel plate supports for test, the beam has a roller connection with plates. These roller supports were installed on concrete members anchored to the strong floor. A concentrated load was applied using manual hydraulic jack, which have a maximum capacity of 320 kN. Zipper bags filled with gypsum was placed in between the roller support and beam to make a smooth contact surface, and also protected the beam from sliding. In this experiment the loading rate was ranged between 0.233 – 1.06 mm/min (0.24 - 0.69 kN/s), which means the loading rate was in between the static and earthquake loading effect. A frame which hold the deflection reading instrument was connected with the rods. This rod was anchored to a beam on both ends by drilling at the axis of rotation. The loading setup is shows in **Figure 3.13**.



Figure 3.13: Loading Setup

### 3.6 Instrumentation

All beams were fully instrumented to measure the applied loads and deflections on the beams. And also the strain was attached on the vertical stirrups. In brief, the instrumentation consisted of a load cell which measures the applied load, deflection measurement tool to measure the mid span deflection and strain gage to measure the strain of vertical stirrups. All of the instrumentations were connected to a data logger and the experimental data was directly obtained in a USB.



a) Displacement measuring tool



b) Load Cell



c) Data Logger



d) Load applying hydraulic jack



e) Strain gage



f) Load system machine

Figure 3.14: Instruments

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## **CHAPTER-4. NONLINEAR 3D SIMULATION OF SHEAR STRENGTHENED RC BEAMS**

### **4.1 Introduction**

Now a day, professionals use nonlinear software's for analysis and design of structures to save their time and to get accurate results. Creation of these advanced software's has an important role in analysis and design of complicated structures with in fraction of seconds. DUCOM-COM3D is a nonlinear software used in this study. All beam types prepared and modified in the experimental program was modeled using this nonlinear software. Modeling of those beam types was the same as experimental in methodology and material properties.

### **4.2 DUCOM-COM3D Nonlinear Analytical Frame Work for RC Beams**

For the analytical simulation of this study, the DuCOM-COM3 software which is developed in the University of Tokyo was used. This is a multi-scale analysis code that links the thermo-chemo-physics platforms DuCOM and COM3. DuCOM is an integrated thermo-hydro analysis code that includes cement hydration in concrete mixture, micro-pore structure formation and mass transport models for concrete ranging from  $10^{-3}$  to  $10^{-9}$  meter scales of micro-voids, while COM3 is a 3D finite-element analysis platform for structural concrete with and without cracks. As a result, DuCOM-COM3 is capable of predicting the change in concrete material properties from casting to dismantling of entire structures and taking this material development into account for predicting the response of structural concrete. With this integration, the long-term structural response under actual ambient conditions can be predicted in a realistic manner.

### **4.3 Three Dimensional Modeling**

The analysis was performed using the multi-directional fixed crack FE framework.

#### **4.3.1 Solid- element and input parameters**

Solid element with eight nodes are used for the simulations. Fixed-four way cracks modeled for concrete is assumed on each plane. Gauss point are defined where the

constitutive laws are integrated. For the different types of material different types of elements are defined.

Reinforced concrete is modeled as solid element with its specific mechanical property and reinforcement ratio. All steel bars were modeled as embedded smeared reinforcement inside the concrete elements. Concrete elements without steel bars were modeled as plain concrete element. Concrete with steel reinforcement was modeled as RC elements characterized by tension stiffening. Elastic material also modeled as a solid element with unyielding behavior. These elastic material element is used to model the loading plates and supporting bearings of the beam. Strengthening rods (shear reinforcement) is modeled as line-element with two nodes. Additional web reinforcement (shear reinforcement) is inserted as a pre-stressed line element and plate used to connect this pre-stress line were modeled as elastic elements.

Table 4.1: Mechanical property for solid elements of reinforcement and elastic materials

Mechanical property	Longitudinal bar	Top reinforcement	Web reinforcement (for normal and pre-stress)	Elastic material
Initial Stiffness (GPa)	196.2	196.2	196.2	206.0
Yield strength (MPa)	648.6	539.4	587.4	-
Tension rupture strength(MPa)	774.2	688.2	706.8	-
Tension rupture strain	0.12	0.10	0.10	-
Poisson ratio	0.20	0.20	0.20	0.20
Unit weight (kN/m <sup>3</sup> )	78.0	78.0	78.0	78.0

Tensile Strength of reinforcement and plate was tested at laboratory. And specimens was modeled in nonlinear finite element software with those material properties.

Table 4.2: Mechanical property for line elements of vertical stirrups

Mechanical property	Shear reinforcement
Stiffness (GPa)	196.2
strength (MPa)	587.4
Initial strain	0.0001
Section area (cm <sup>2</sup> )	0.1965
density(kN/m <sup>3</sup> )	78

Initial strain was intentionally given to the vertical stirrups in both programs (experimental and software) to tie the beam initially by stirrups. A  $100\mu\epsilon$  was given to vertical stirrups to avoid more gaps between the beam and stirrups.

Table 4.3: Mechanical property for solid element of concrete

Mechanical property	Specimen							
	Phase-1							Phase -2
	Beam Type-1	Beam Type-2	Beam Type-3	Beam Type-4	Beam Type-5	Beam Type-6	Beam Type-7	All beam type
Initial Stiffness (GPa)	25.2	23.9	26.7	26.2	24.4	23.7	25.2	25.2
Compressive strength(MPa)	30.4	26.1	35.4	27.7	33.7	25.6	30.4	30.4
Tensile strength (MPa)	2.93	2.71	3.16	2.80	3.08	2.69	2.93	2.93
Poisson's ratio	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Unit weight (kN/m <sup>3</sup> )	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5

Compressive Strength of specimen cubes and tensile strength of cylinders were done in laboratory. Those properties and other listed above in **table 4.3** was used in the simulation software to verify the experimental results. Corresponding material properties was used to model each beam in analytical simulation software.

### 4.3.2 Modeling different shear strengthening techniques

Three-dimensional nonlinear finite element analyses were carried for two phases of specimens. In phase-1, the material properties of specimens modeled in Ducom-Com3 were similar with their respective experimental material properties. In phase-2 unlike in phase-1, specimens were modeled in Ducom-Com3 having the same material property to check the effect of additional web reinforcement configurations. The specimens were modeled in the finite element software depending their respective shear strengthening techniques as shown in **figure 4.1 and 4.2**.

Table 4.4: Specimens Description

Specimen	Additional web reinforcement	Configuration of web reinforcement	Phase-1 measured com. strength (MPa)	Phase-2 compressive strength (MPa)
BEAM TYPE-1	-	-	30.4	30.4
BEAM TYPE-2	Ø5c/c130mm	External stirrups provided	26.1	30.4
BEAM TYPE-3	Ø5c/c130mm	Internal provided stirrups with horizontal leg	35.4	30.4
BEAM TYPE-4	Ø5c/c130mm	Internal provided stirrups without horizontal leg	27.7	30.4
BEAM TYPE-5	Ø5c/c130mm	Internal provided stirrups without horizontal leg	33.7	30.4
BEAM TYPE-6	Ø5c/c130mm	Concrete cover grooved and provided stirrups	25.6	30.4
BEAM TYPE-7	Ø5c/c130mm	Normal internally provided stirrups	-	30.4

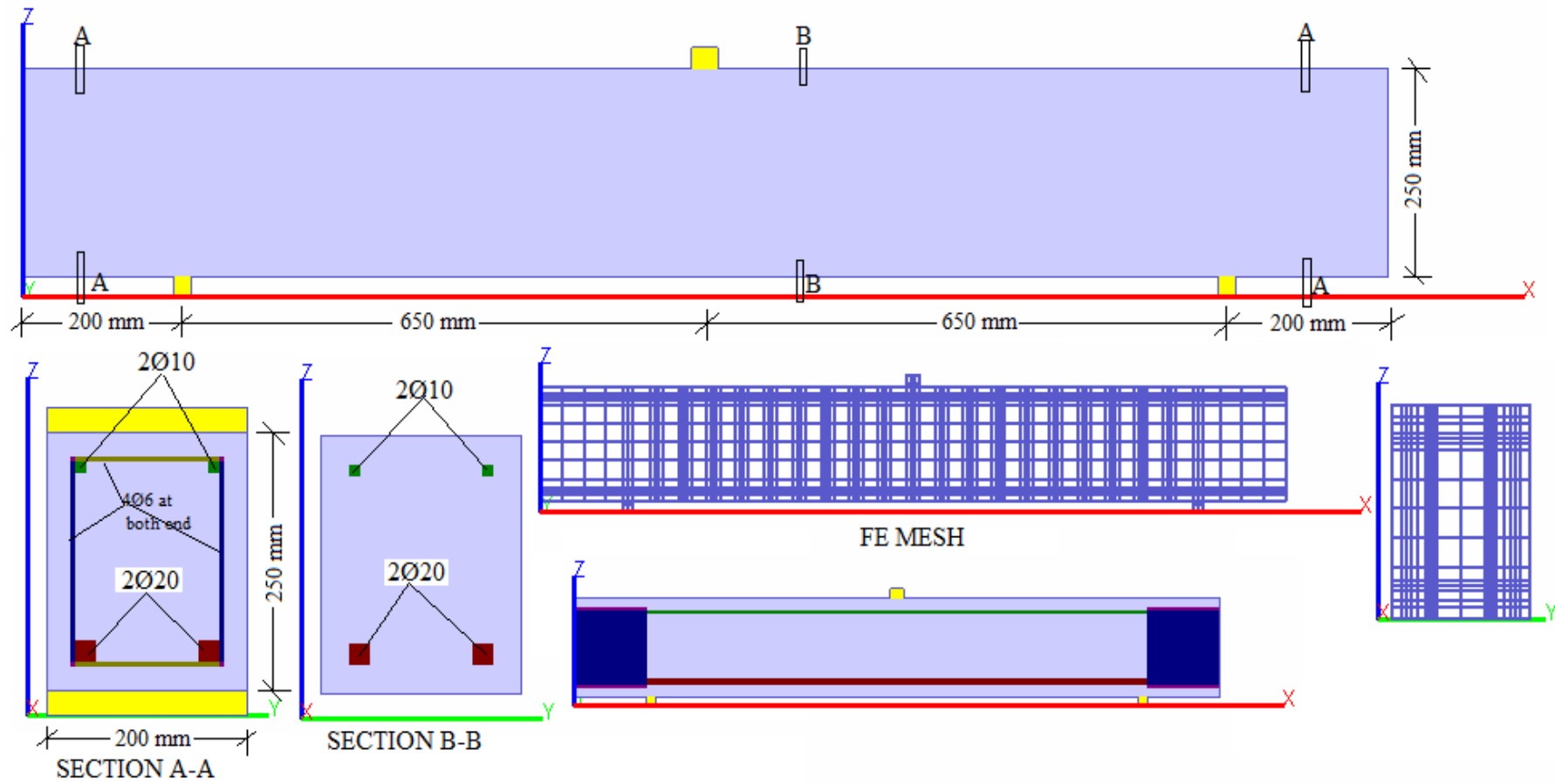


Figure 4.1: Beam Type-1 and Model Representative of Other Type of Beams

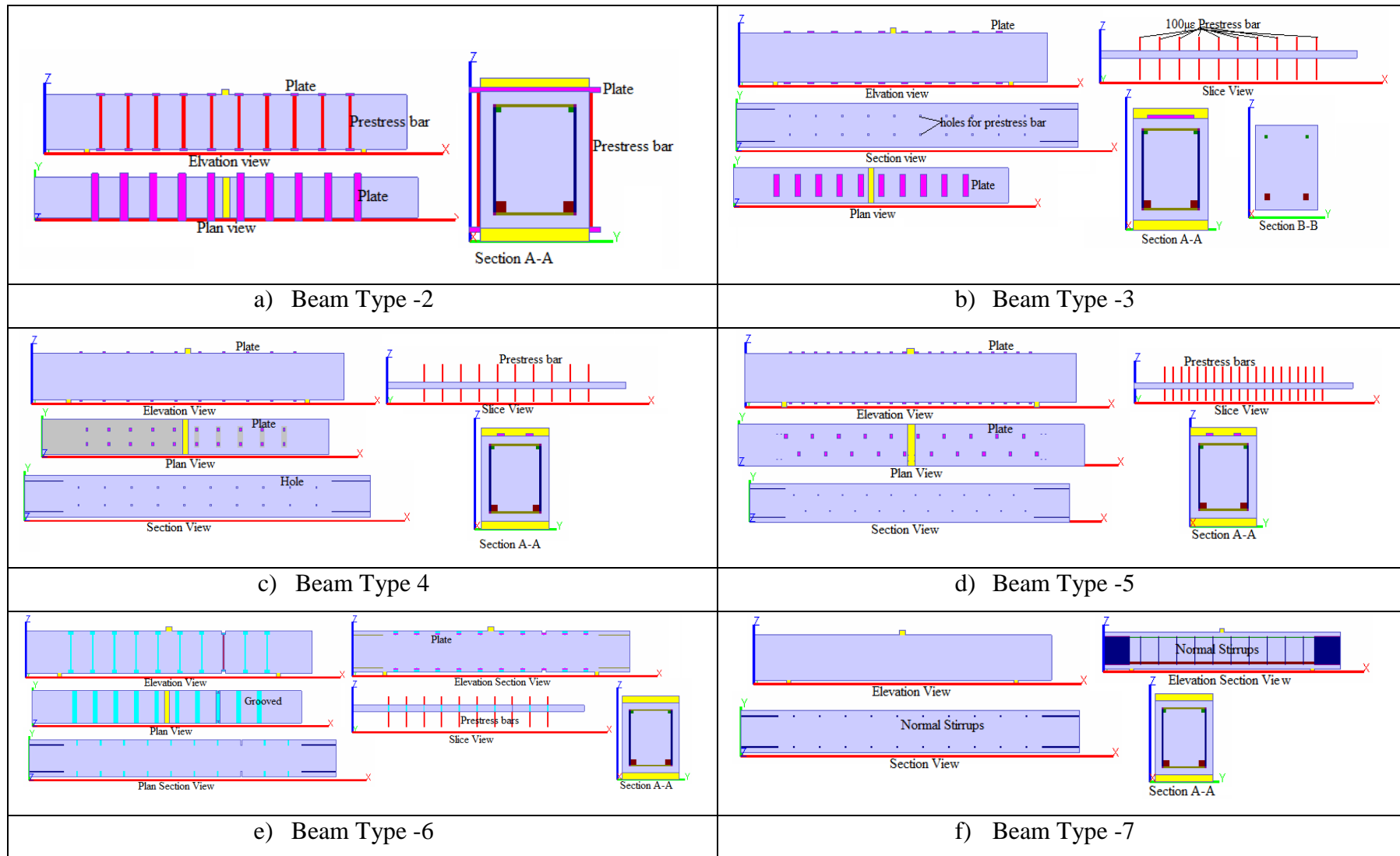


Figure 4.2: Beam Types and Additional Web Reinforcement Configurations

### 4.3.3 Boundary conditions

The beams were simply supported with 1.3 m clear distance between the supports. Elastic bearings were used at the support and at the point of load application in the mid span. The beam was modeled with roller support on one side and pin support conditions on the other side. The beam was restrained on one side of the support along x direction only (roller support model) but on the other side support the beam was restrained in two directions along x and z-direction (pin support model). The plate at mid span used to apply load was restrained in z-direction, to capture the post peak behavior of the beams. Displacement controlled analysis was performed by applying a downward displacement of 0.065 cm per minute for 30 load steps at the mid span. Displacement controlled load was induced to capture the post-peak response of the reinforced concrete beams.

## 4.4 Constitutive Laws for Concrete

### 4.4.1 Tension

Concrete compressive strength of the specimens was determined from the experiment. Tensile strength and Modulus of elasticity of the concrete were calculated by a formula recommended in **ACI (committee 363)**. To use a uniform formula expressions for all tensile strength of concrete beams, the average laboratory tensile strength was compared with new design code of Ethiopia and ACI formula ( $0.59\sqrt{f'_c}$ ). Both codes gave a good approximation value to the laboratory splitting tensile strength of concrete result. But the new design code of Ethiopia was not expressed in formula form, it simply listed the values in table. So in this study the ACI formula is used to quantify splitting tensile strength of concrete. This result is consistent with model code recommendation for relating the tensile splitting strength with that of uniaxial tensile strength.

Table 4.5: Tensile Strength for 25.6 cylindrical compressive strength

Type expression	Tensile strength(MPa)
New design of code Splitting tensile strength ( $f_{ctm}$ ) (no formula)	2.92
Splitting tensile strength ACI code	2.98
Average Laboratory Splitting tensile strength for 3 cylinders	2.91

$$f_{tsplitting} = 0.59\sqrt{f'c} \text{ MPa} \dots\dots\dots(1)$$

$$f_{ttensile\ strength} = 0.9 * (0.59\sqrt{f'c}) \text{ MPa}$$

$$Ec = 3320\sqrt{f'c} + 6900 \text{ GPa} \dots\dots\dots(2)$$

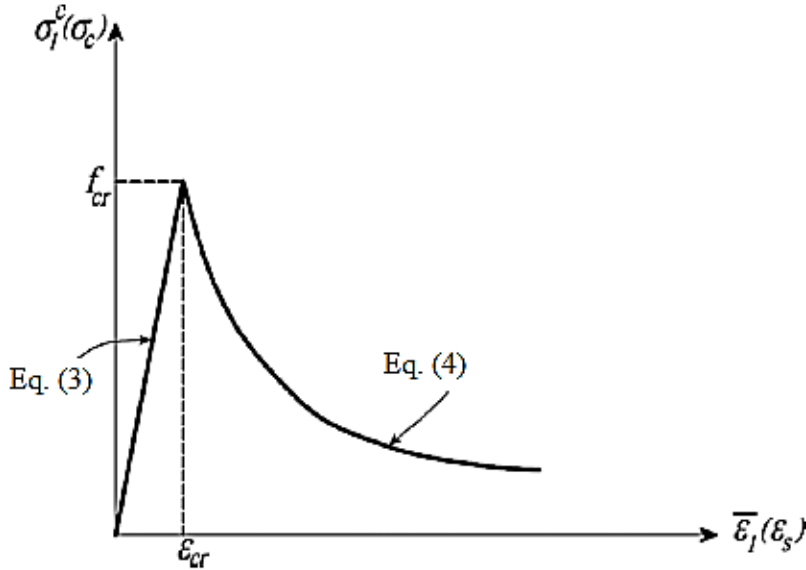


Figure 4.3: Tensile Stress-Strain Curve of Concrete

$$\sigma_1^c = E_c \epsilon_1 \dots\dots\dots (3)$$

$$\sigma_1^c = f_{cr} \left(\frac{\epsilon_{cr}}{\epsilon_1}\right)^{0.4} \dots\dots\dots (4)$$

In this modeling the tension softening/stiffening factor ratio was taken as two for plain concrete and 0.4 for reinforced concrete. The value of the tension softening factor for plain concrete is size dependent (Bazant) however in the current case a value of two is assumed for simplicity.

**4.4.2 Compression**

The primary characteristics of the constitutive law of concrete in compression is the softening of peak stress in comparison to the companion cylinder. The variables of method strengthening and configuration of shear stirrups was affect the softening phenomenon. The softening coefficient was also found to be inversely proportional to  $\sqrt{f'c}$ .

#### **4.4.3 Shear-constitutive law (contact density based)**

Various models have been proposed for the shear constitutive law of concrete. The two phase modeled and the contact density model are among the widely used models on nonlinear analysis of reinforced concrete. For the purpose this research, the contact density model, where the roughness of cracked concrete is described through a contact density function. The details of the model are elaborated in K.Maekawa, 2003.

Shear in reinforced concrete was investigated both theoretically and experimentally in this research. A literature review revealed that shear in reinforced concrete was not well understood, even though it has been studied for almost a century. The modeling was tested with technique types and shear stirrups configuration as a major variables. The constant variables of the modeling were: a concrete strength of 30.4 MPa, a steel yielding strength of 648.6 MPa and a rebar spacing of 130 mm. The test results indicate that the constitutive laws of both steel and concrete struts were significantly “softened” in cracked reinforced concrete, resulting in a set of average softened stress-strain relationships of steel and concrete.

#### **4.5 Loading and Interpretation of Results**

Displacement controlled load was induced to capture the post-peak response of the reinforced concrete beams. The displacement is apply to the beam as a time step type of loading. And as a result the nonlinear finite element software gives a respective responses of every elements. In this nonlinear simulation software the local response of every beam elements was describe using different colors. But in this research to compare the analytical and experimental results only load and deflection of mid span was taken.

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## CHAPTER-5. EXPERIMENTAL RESULTS AND DISCUSSION

### 5.1 Introduction

For all beam types their result was discussed in the following sections. All strengthening techniques are effective in shear strengthening of reinforced concrete beams. All strengthening techniques were compared relative to control beam, which is a base line of strengthening techniques, using actual and normalized compressive strength of a concrete as listed in **table 5.1**. And also the effectiveness of shear stirrups was quantified among the strengthening techniques by neglecting the shear capacity of concrete.

### 5.2 Experimental Result

The experimental results indicate that addition of shear stirrups on existing beams was an effective method of shear strengthening. The effectiveness of these shear stirrups was depend on their configuration and orientation type. All beams were intentionally designed to fail in shear. As a result, all beam failed in diagonal shear as shown from **figure 5.1 - 5.6**. The beams are designed to have 3.11 shear span to effective depth ratio. Diagonal cracks of control beams and the strengthened beams were observed to be typical diagonal crack of a slender beam.

#### 5.2.1 Ultimate Loads and Comparisons

The ultimate loads of all beam types and the relative strength of strengthened beams to control beam (Beam Type-1) are listed in **table 5.1**. Control beam is a base line of other beam types. By normalizing compressive strength the relative strength of strengthened beams to control beam (Beam Type-1) was also quantified in **table 5.1**. This normalization is used to avoid the difference in compressive strength values of different beams.

Among the six beam types, Beam Type-1 was a control beam which was not strengthened. Beam Type-1 (1) failed at a maximum load of 134.6 kN in shear with the formation of a diagonal crack at mid shear span in one side only. Beam Type-1 (2) failed at an ultimate load

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of 127.6 kN by developing a diagonal shear crack at mid shear span in both sides. The measured compressive strength values for type-1(1) and type-1(2) are 34.1 and 26.7 MPa respectively.

Beam Type-2 was strengthened with external stirrups provided along shear span as shown in **figure 5.2**. Beam Type-2 has two beam samples and both beams failed by propagated a diagonal shear crack in both sides at mid shear span. Beam Type-2(1) and Type-2(2) failed at a load of 179.6 kN and 200.8 kN respectively. The measured compressive strength values for type-2(1) and type-2(2) are 23.9 and 28.4 MPa respectively. This technique (beam type-2) enhance the shear capacity of beam by an average of 45.1% than control beam.

In Beam Type -3 the beam was strengthened by drilling and inserted vertical legs through the core concrete. The vertical leg stirrups were connected with horizontal plates using bolting to enhance the confinement. This beam type failed at an ultimate shear load of 226.6 kN and the hair like of shear cracks were propagated along both sides of shear span. The measured compressive strength values for this beam type is 35.4 MPa. This beam type was 72.9% higher in shear capacity than Beam Type-1.

In Beam Type-4 and Beam Type-5, horizontal plates was not provided unlike that of Beam Type-3. Beam Type -4 and Beam Type-5 were strengthened by inserted vertical legs only along drilled depth of beam with parallel and staggered hole configurations respectively as shown in **figure 5.4 and 5.5**. Beam Type-4 and Type-5 failed at a load of 166.6kN and 182.6 kN respectively. The measured compressive strength values for type-4 and type-5 are 27.7 and 33.7 MPa respectively. Beam Type-4 and Beam Type -5 are techniques enhance the shear capacity of beam by 27.1 and 39.3 % than control beam respectively.

Beam Type-6 was strengthened by inserted the vertical leg stirrups and horizontal plate through the grooved section of the beam as shown in **figure 5.6**. In this beam type the hair like shear crack was started at grooved shear span, which were not filled and left for strain gage. And then the crack were propagated in two sides along critical shear sections. This beam type failed at an ultimate load of 157.3 kN. The measured compressive strength values for this beam type is 25.6 MPa. This beam type was 20.0% higher in shear capacity than the control beam.

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### 5.2.2 Effectiveness of additional web reinforcements and comparisons

The efficiency of web reinforcement was quantified by neglecting the shear capacity of concrete ( $V_c$ ). Efficiency of web reinforcement depends on strengthening and configurations types' as listed in **table 5.2**. The efficiency of strengthened beams was also quantified relative to conventional web reinforcement design.

Beam Type-2, external shear stirrups provided along shear span, has an average of 16.2% lesser in shear stirrups efficiency than the conventional shear reinforcement design ( $V_s$ ). This beam type was an average of 22.0 % and 77.7% higher in shear stirrups efficiency than beam type-5 and beam type-6 respectively.

Beam Type-3 was higher than the conventional web reinforcement design by 22.4% in shear capacity. It was also 46.0% higher in efficiency of stirrups strength than Beam Type -2. The ultimate tensile strength of shear stirrups was 775.2 MPa. This beam type has a 7.0% reduction in capacity when analysis using ultimate tensile strength. Interestingly, three stirrups at critical shear section were cutoff at the same time including the stirrup with strain gage.

Beam Type-4 and Beam Type -5 was 51.8% and 31.3% lesser in shear stirrups efficiency than the conventional shear reinforcement design ( $V_s$ ) respectively. Beam Type-4 and Beam Type-5 are 60.6% and 43.8% lesser than Beam Type-3 respectively in shear stirrups efficiency. Beam Type-5 has 42.5% higher in shear capacity than Beam Type-4. In these beam types the shear cracks was developed along the critical shear section in both sides and some stirrups were cutoff. These beam types does not have a horizontal plates and as a result these beams loss the strength came due to confinement. So these beams were reduced their strength than Beam Type-3 due to confinement effect.

Beam Type-6 has 23.3% lesser in shear stirrups efficiency as compare to conventional web reinforcement design. Beam Type-3 and Beam Type-4 was 159.4% and 2.3% higher in shear stirrups efficiency than Beam Type-6 respectively.

a) Beam Type-1(1)



a) Beam Type-1(2)



Figure 5.1: **Beam Type-1(Control Beams)**

a) Beam Type-2 (1)



## b) Beam Type-2 (2)



Figure 5.2: External Stirrups Provide along Shear Span (Beam Type-2)



Figure 5.3: Parallel Vertical Stirrups and Horizontal Plate Provide along Shear Span by Drilling (Beam Type-3)



Figure 5.4: Parallel Vertical Stirrups only Provide along Shear Span by Drilling (Beam Type-4)



Figure 5.5: Staggered Vertical Stirrups only Provide along Shear Span by Drilling  
(Beam Type-5)



Figure 5.6: Vertical Stirrups and Horizontal Plate Inserted In the Grooved along Shear  
Span (Beam Type-6)

### 5.2.3 Load–deflection behavior

Figure 5.7 indicated that all strengthened beams were resisted more load than the control beam. The largest load occurred in Beam Type-3, where the beam strengthened by inserting parallel vertical stirrups and horizontal plate used to connect the vertical legs using bolting. Beam Type-1(1) and Beam Type-1 (2) were failed in lesser loads, whereas the other beams failed in a relatively higher loads. Generally, Beam Type-3 have higher shear resistance than other beam types. Beam Type-6 is less effective method of strengthening among the strengthened techniques.

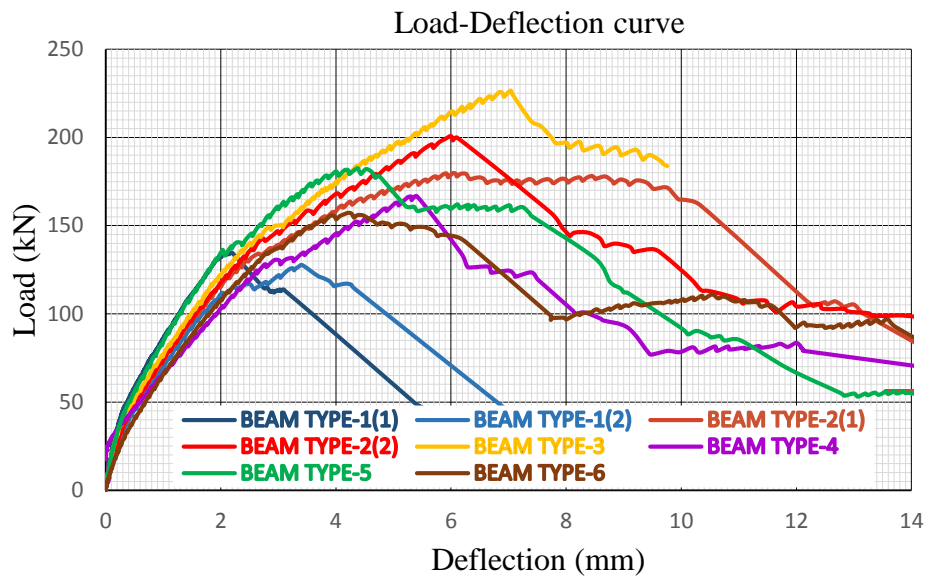


Figure 5.7: Load Deflection Curve

### 5.2.4 Load-strain behavior

Figure 5.8 showed that the strains measured in the vertical stirrups at critical shear span. Initially an average of 100 (0.81 kN) micro strain were given to vertical stirrups. First the coming load is resist by the concrete and when the load is exceeded the capacity of concrete, the stirrups start mobilize to carry the load. When the stirrups start to carry the load the strain of stirrups starts to increases. When the stirrup fails the strain terns back.

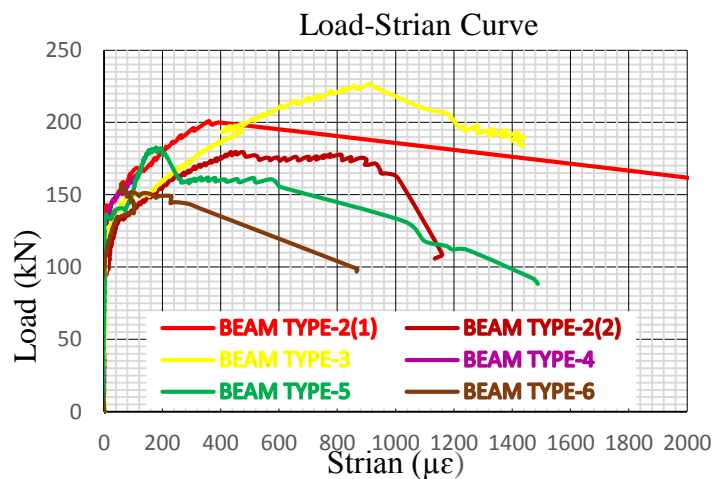


Figure 5.8: Load-Strian Curve

Table 5.1: Relative Strength and Failure Mode

Type of Beam	Strengthen scheme	Ult. Load (kN)	Vc, theo. (kN)	Relative Strengthen	Normalized	Mode of failure
Beam Type-1	Control beam	131.1	141.3	1.00	1	Shear failure
Beam Type-2	Externally shear stirrups provide along shear span	190.2	-	1.45	1.38	Shear failure
Beam Type-3	Internally shear stirrups provide in shear span by drilling along depth of beam and tie with horizontal using bolting	226.6	-	1.73	1.81	Shear failure
Beam Type-4	Only vertical shear stirrups provide internally along shear span by drilling and parallel in configuration	166.6	-	1.27	1.23	Shear failure
Beam Type-5	Only vertical shear stirrups provide internally along shear span by drilling and staggered in configuration	182.6	-	1.39	1.45	Shear failure
Beam Type-6	shear stirrups provide on grooved section of concrete cover using bolting	157.3	-	1.20	1.12	Shear failure

Table 5.2: Effectiveness of additional shear stirrups relative to conventional shear stirrups design

Type of Beam	Diag. crack (kN)	Ult. Load (kN)	Vc, exp (kN)	Vs, exp (kN)	Vs,theo. (kN)	Ratio (Vs,exp/ Vs,theo.) (%)
Beam Type-1(1)	130.8	134.6	134.6	-	-	-
Beam Type-1(2)	115.3	127.6	127.6	-	-	-
Beam Type-2(1)	121.3	179.6	124.1	27.8	37.1	74.9
Beam Type-2(2)	126.1	200.8	132.1	34.4	37.1	92.7
Beam Type-3	128.1	226.6	135.8	45.4	37.1	122.4
Beam Type-4	128.1	166.6	130.8	17.9	37.1	48.3
Beam Type-5	125.1	182.6	131.6	25.5	37.1	68.7
Beam Type-6	118.1	157.3	122.3	17.5	37.1	47.2

---

### 5.3 Elaboration of Experimental Results

As shown in **table 5.2**, the effectiveness of web reinforcement in Beam Type-2 was lesser than conventional web reinforcement design. In this method of strengthening, both vertical and horizontal shear stirrups were externally provided on the beam. However, vertical stirrups were very difficult to tie closely on beam surface without small gaps. So there were a small gap between vertical stirrups and beam face. This small gaps made both vertical and horizontal stirrups to bend as shown in **figure 5.9**. Therefore, the vertical stirrups were subjected to both bending and tension actions but shear stirrup was designed to tension action only. As a result both actions were reduced the capacity of vertical stirrups.

Beam Type-4 and Beam Type-5 were lesser in shear stirrups efficiency than conventional web reinforcement design. In these beam types, horizontal shear legs were not provided so those beams was resist lesser load due to absence of confinement. Shear stirrups on parallel sides were subjected to different strains at the same time as shown in **figure 6.3**. This difference in strains were cause small torsion on the beam. Because of the absence of horizontal legs, vertical legs were resist separately the coming shear loads. As a result of those reason, the shear capacity of these beam types were reduced. Beam Type-4 has less shear resistance capacity than Beam Type-5. Beam Type-4 has parallel stirrups configuration but Beam Type-5 has staggered stirrups configuration type. Staggered configuration type of shear stirrups has grater shear length crack than parallel configuration type. This longer in length crack, were increase the inclined shear area of the beam and higher in shear capacity. In addition to this the shear stirrups were nearly distributed in staggered stirrup configuration type.

Beam type-3 was more confined as compare to beam type-5 and this confinement in concrete make stronger in shear resistance capacity. Beam type-3 has higher shear resistance capacity than conventional web reinforcement design. This higher value was coming as a result of the following reasons. In this study an average tensile strength of shear stirrups but it was probability to get average tensile strength. In addition to this, rigidity of horizontal plate also have a great role on the increment of shear stirrups efficiency. This rigidity help to carry all the load by vertical leg of shear stirrups and these vertical legs used their full capacity or ultimate strength (775.2 MPa). Horizontal plate had a role to increase the confinement effect

of concrete. As a result of these reason this type of beam was most effective and higher in failure load.

Beam Type-6 has lesser in shear resistance capacity than conventional web reinforcement design. This beam type was strengthening with both vertical and horizontal legs, and these shear stirrups were tight on the grooved section of beam. After provided the shear stirrups, the grooved section was filled with mortar cementing materials. But among the ten grooved areas one was not filled with cementing materials to connect the strain gage on vertical stirrups. But the filled mortar do not made a bond like the existing one. This beam also share the effect on Beam Type-2 in tying of shear stirrups. Therefore, this beam had lesser in shear capacity as compare to conventional web reinforcement design.



a).



b).

**Figure 5.9: Twisting of Vertical and Horizontal Legs**

All Beams are designed with same specifications as described in the experimental strategy. But these beams were modified using different methods to have different shear strengthening techniques. During this modifications there are some situations occur and these situations are uncontrollable or unavoidable. These conditions was made a background assumptions of this research and their effect were neglected. The following are background assumptions and their effect was neglected during discussing result of beams:

- Reduction of cross section due to the created hole
- Effect of vibration when drilling
- Bond of inserted vertical stirrups with existing concrete

To study those effects purposely one beam was prepared, which was identical specification to the other beams, to test the validation of the assumptions. This validation were checked using a beam holed (drilled) on one side of shear span and undrilled on the other side of shear span as shown in **figure 5.10**. Those drilled and undrilled shear spans of a beam were anchored externally using stirrups, as Beam Type-2, to observe the cracks evidently and to quantify how much greater one from the other shear span. Cracks occur approximately in the same load but the shear span with holes were 5% higher than shear span without holes. Shear span with holes create a diagonal crack at load of 146 kN but a shear span without holes create diagonal crack at load of 131 kN. This variation came due to presence of holes. Holes vanish the coming concentrated shear force and delaying the time to pass across the holes or crack. This delaying in time makes the section to carry more loads in shear. So that the assumptions were correct.



Figure 5.10: **One Side of Shear Span Drilled and the Other Side Undrilled Beam**

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## CHAPTER-6. VERIFICATIONS OF EXPERIMENTAL RESULTS USING SIMULATION SOFTWARE

### 6.1 Introduction

It difficult to examine beams always in experimental program. This because of its difficultness of controlling all parameters, its expensiveness and its wasting of time in experimental program. So experimental results should be verify using nonlinear finite element software's to avoid the above limitations. After verification of the experimental results, the nonlinear finite element software's use to check the effectiveness of shear stirrups configuration types using the same material properties. And also this software uses to quantify the effect of holes on a beam and the initial strain on a vertical stirrups in shear resistance capacity.

### 6.2 Analysis Simulation Result Using Actual Mechanical Property (phase-1)

Six beams were modeled on analytical simulation software (DuCOM-COM3) with identical material properties of experimental beams. All beam types were modeled in the software with their corresponding mechanical property of the experimental conditions. This was done to verify the experimental result using analytical simulation software. As in experimental failure mode, the simulated beams were failed in shear as shown in **figure 6.1**. So their general mode of failure property were the same as the experimental result.

Beam Type -3 and Beam Type -5 had higher failed load than other beam types. Like the experimental result, Beam Type-6 was resist a lesser shear load among other strengthened beam types. The load-deflection diagram for the specimens is shown in **figure 6.2**. Unlike the manual work, analysis using software were more precise. This perfection of loading system makes Beam Type-5 as effective as Beam Type-3 in the analytical simulation, unlike the experimental result.

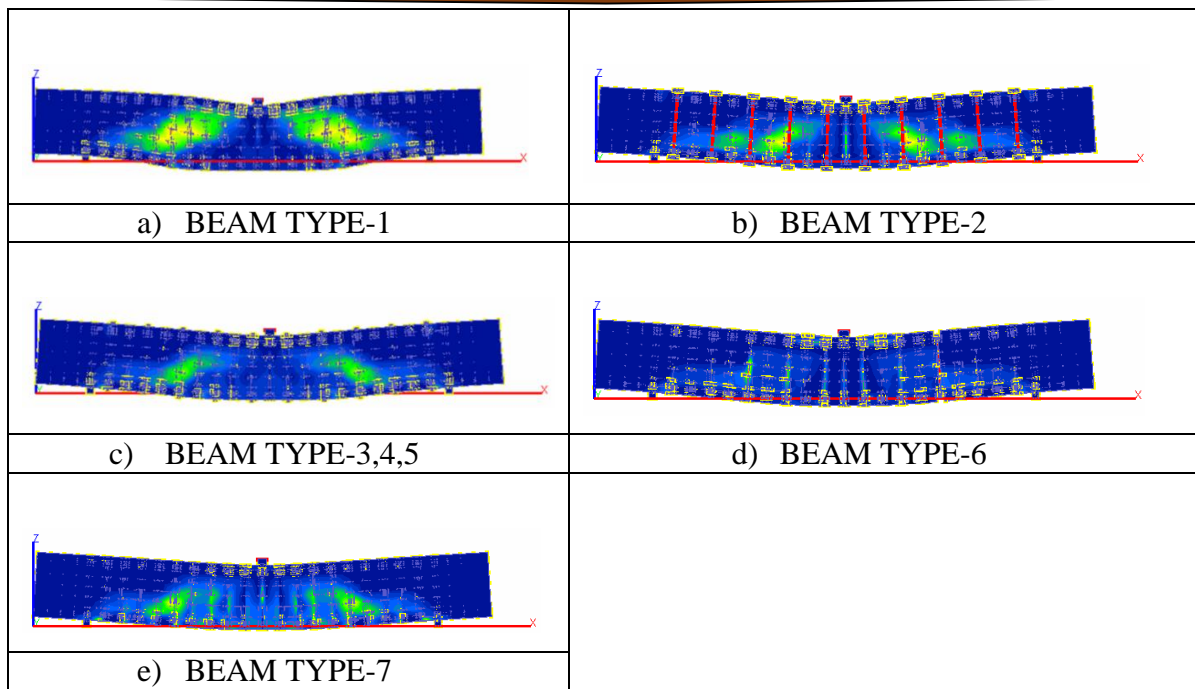


Figure 6.1: Failure Mode of Finite Element Analysis

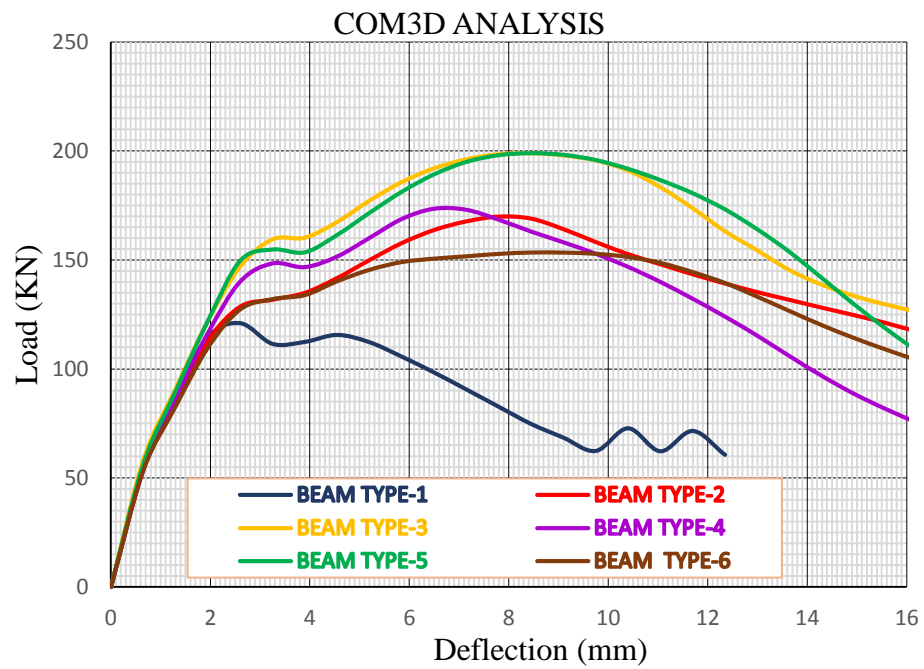


Figure 6.2: Summary of Load-Deflection Diagram from the Finite Element Analysis

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### 6.3 Comparison between Experimental and Analytical Simulation Results

Simulation on DuCOM-COM3 involved 6 beams to compare the experiment and analytical result. The specimens used in the finite element modeling were identical to the specimen's properties of experimental program. So it is easy to compare the same strengthening techniques in analytical and experimental programs.

Generally both result, experimental and analytical result, are consistent in mode of failure and load-deflection curve. Experimental and analytical simulation result were quit similar in slope up to diagonal crack occurs. After the diagonal crack occurred shear stirrups were start to carry loads, at that time the load-deflection slope was started to deviate. This divergent in slope of load deflection among experimental and analytical result was came due to mechanical properties of steel. And this variation was come as a result of the following reasons. One for the experimental program an average of yielding strength of web reinforcements was taken, but their laboratory test result was gaped range in yielding strength. Secondly, in concrete the modulus of elasticity was calculated from their respective compressive strength but modulus of elasticity of steel was taken from material fabrication property.

Beams strengthened with vertical stirrups only has higher analytical simulation result than experimental. This was due to the perfection of loading system in analytical simulation. Strain gages were give a good solution for this variation as follow. Intentionally, in the experimental beams there were attached two strain gages parallel in position, one on left and the other on right side, at shear critical to measure the strain of web reinforcements. But their strain were quite different in result on both parallel sides with in the same time as shown in **figure 6.3**. This result was came due to manual imperfection work in experimental loading system of beams, because loading was done manually using hydraulic jack. So this small imperfection creates an eccentric load (torsion) with respect to longitudinal axis of a beam and this makes different in result of web reinforcement strain on parallel sides with in the same time. This variation in strain indicated that vertical legs in parallel side had carry different loads in magnitude. In experimental test, vertical legs on parallel side cannot balance each other. So in these beams full capacity of vertical stirrups does not use unlike of the analytical beams. But in analytical result the loading system was very perfect, does not make any eccentric load

on the beams so use full capacity of vertical stirrups. Consequently, the analytical result were greater than experimental result for these beams.

Strengthened beam types with vertical and horizontal stirrups (plates) were had higher experimental result as compare to the analytical simulation result including control beam (Beam Type-1). The reason makes higher in experimental result was discussed as follow. In this study used an average yielding tensile strength but it was a probability to get an average tensile strength in experimental beams. As a result of this reason, the experimental result was higher than analytical result.

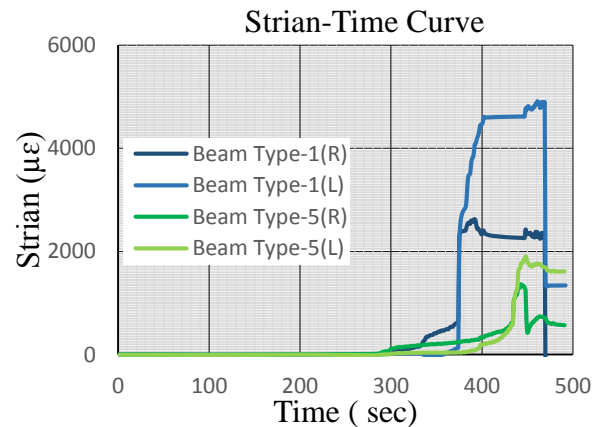
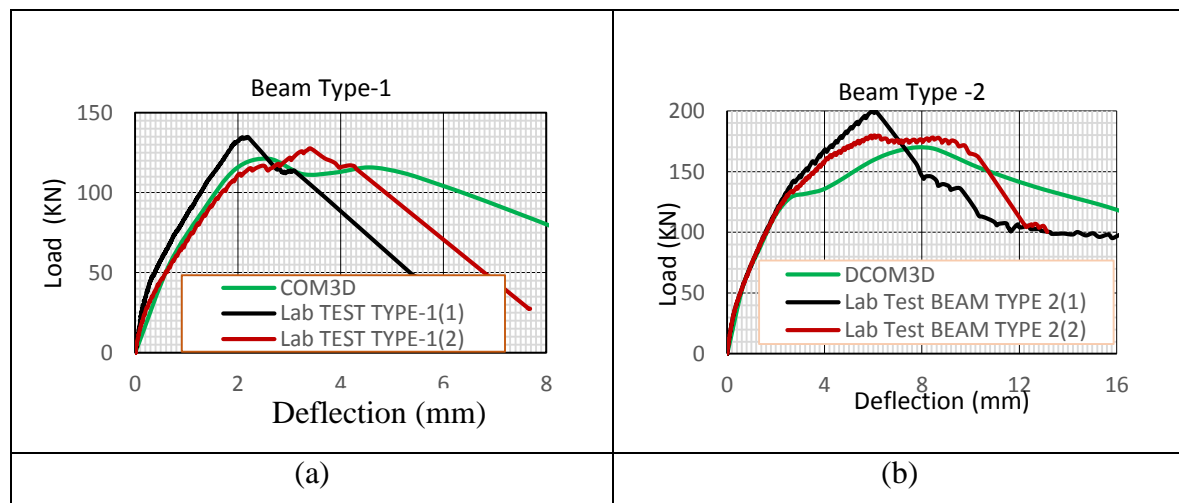


Figure 6.3: **Strain-Time Curve**

Comparison of load- deflection diagram for these six specimens between experimental and analytical results is shown in the figures below.



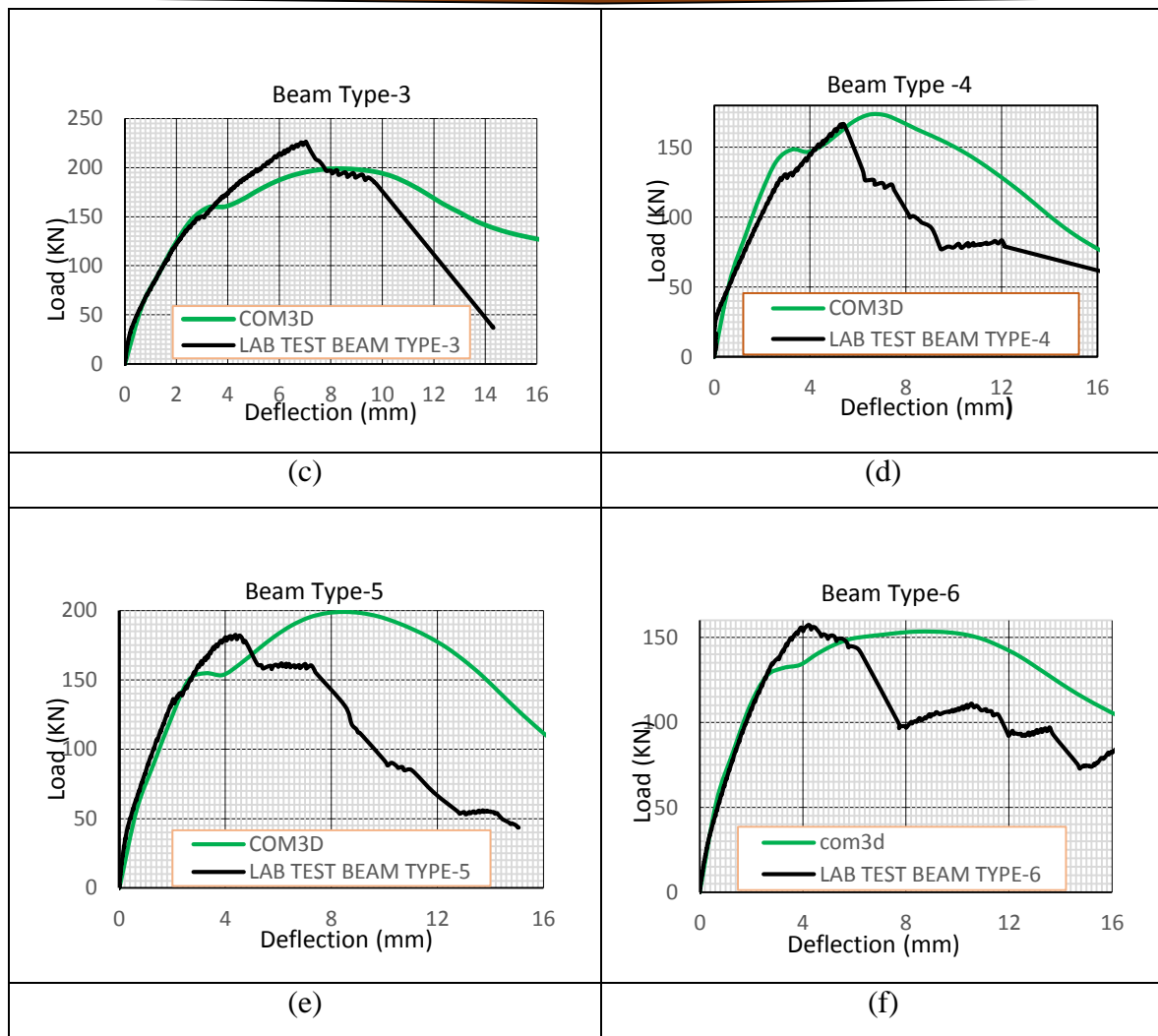


Figure 6.4: Load – Deflection Diagram

## 6.4 Uses of Verified Simulation Software

From **section 6.3** the analytical and experimental results are consistent. So this nonlinear finite element software can be used in other analyses which are not addressed in the experimental program. This verified nonlinear finite element software was used to study the effect of web reinforcement configuration, holes in beams and initial strain of vertical stirrups.

### 6.4.1 Effect of web reinforcement configuration (phase-2)

In this phase, seven beams were modeled on analytical simulation software (DuCOM-COM3). All beams are modeled with identical material properties to investigate the effects of

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web reinforcement configurations. This phase avoid the shear resistance capacity due to difference in compressive strength of concrete. So in this phase, the only difference was a web reinforcement configuration by making other parameters constant, like material mechanical properties and loading conditions. Effectiveness of additional web reinforcement configurations were a critical concept in this section. In this section the exactness of load application point and uniformity of material were the most criteria that vary the value of experimental and analytical simulation software results.

Generally, all web reinforcement configuration types were effective in shear strengthening of beam. Beam Type-3 and Beam Type-5 were the most effective method of strengthen among other strengthened types. Beam Type-6 was less effective method of strengthening among the other strengthening types as shown below in **figure 6.5**.

The conventional web reinforcement design (Beam Type-7) was 10.6% lesser in capacity than zigzag configuration type of web reinforcement (Beam Type-5). The zigzag type of web reinforcement configuration increase the path length of diagonal crack, as a result this path was increase in inclined shear area of the beam. Increase in inclined shear area is directly relationship with shear resistance capacity of a beam. And also Holes vanish the coming concentrated shear force and delaying the time to pass across the holes or crack. This delaying in time makes the section to carry more loads in shear as shown in **figure 6.6**. In addition to this, the shear stirrups were nearly distributed in staggered stirrup configuration type along critical shear span. So it is reasonable to have beam type-5 a greater failure load than conventional internal web reinforcement design.

Beam Type-3 is higher in resistance of shear capacity than Beam Type-7. This effect is due to presence of hole on beam type-3. Consequently, Beam Type-3 resist higher load than conventional web reinforcement design (Beam type-7).

Table 6.1: Capacity of provided stirrups and failure mode

Specimens	Failure load (kN)	strengthening load using additional stirrups (kN)	Increment from control beam (%)	Relative Strengthen to control beam	Compare with monolithically casting (Beam Type -7) (%)	Mode of failure
Beam Type -1	121.04	-	-	1	-	shear failure
Beam Type -2	179.7	58.66	48.46	1.48	95.29	shear failure
Beam Type -3	187	65.96	54.49	1.54	107.15	shear failure
Beam Type -4	184.3	63.26	52.26	1.52	102.76	shear failure
Beam Type -5	189.1	68.06	56.23	1.56	110.56	shear failure
Beam Type -6	164	42.96	35.49	1.35	69.79	shear failure
Beam Type -7	182.6	61.56	50.86	1.51	-	shear failure

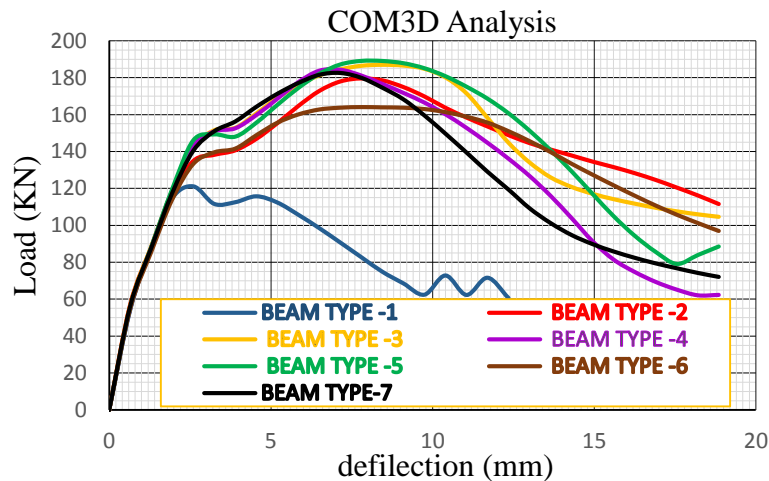


Figure 6.5: Summary of Load-Deflection Diagram from the Finite Element Analysis

#### 6.4.2 Effect of holes and pre-strained stirrups on beams

Beams were modeled in the software to know the effect of holes and pre-strain variation of stirrups on beams. This concept was a good input for the experimental beams.

In this case two beams were modeled on the software with and without holes. The hole size was 10mm in diameter, which was the same size as the drilled holes in the experimental. Beam

with holes had relatively a higher value in shear resistance capacity. These holes distribute or vanish the coming shear forces, as a result the shear crack takes a time to pass along the holes. This time extension, helps the beam to have a relatively higher carrying load as shown in **figure 6.6**. So these small holes on beam have a positive role on shear resistance of a beam.

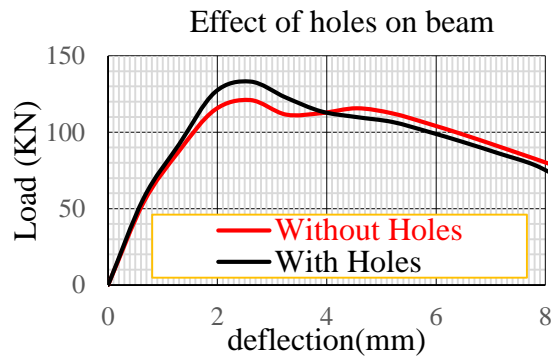


Figure 6.6: **Load – Deflection Curve of a Beam with and Without Holes**

Three beams were simulated in the software to investigate the effect of initial pre-stress (pre-strain) given to vertical shear stirrups. Variations of initial pre-strain on shear stirrups does not have any effect on the ultimate failure load, but this variation in initial pre-strain have an effect on initiation of diagonal cracks. Shear stirrups with higher initial pre-strain have relatively higher diagonal cracking load, because the pre-strained stirrups have a contribution on carrying of load before diagonal crack occurs. Therefore, this pre-strain of stirrups helps the beam to create a diagonal crack at relatively higher loads as shown in **figure 6.7**.

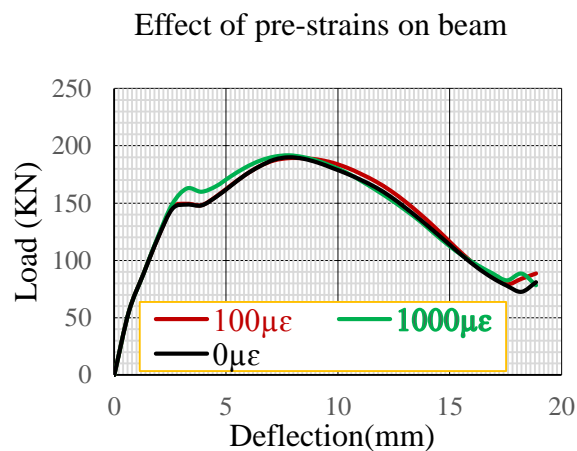


Figure 6.7: **Load – Deflection Curve of a Beam with Different Pre-Strains**

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## CHAPTER-7. CONCLUSION AND RECOMMENDATION

### 7.1 Conclusion

In this research, different techniques were used to strengthen shear critical reinforced concrete beams. Experiment and software simulation programs were used to perform the effectiveness of strengthening techniques. A total eight experimental beam samples and 16 software simulated beams were used in this study. Different techniques were utilized by introducing web reinforcements externally and internally. The relative efficiency of the various strengthening mechanisms through different configurations were examined. And configuration type have a positive role on shear capacity.

Generally nonlinear finite element analysis was found consistence result with that of experimental in mode of failure and load –deflection curves. In both result the load-deflection curve from origin to diagonal crack occurs ,the slope of load-deflection curve laps each other and then after a crack occurs their slope was somewhat deviating. Result of experimental and software simulated beams shows that, all strengthening techniques were effective in shear improvement of a beam. From experimental result, Beam Type-3 was the most effective method and Beam Type-6 was less effective method of strengthening techniques. Interestingly, internal drilled with horizontal leg (Beam Type-3) was the most effective method due to hole and confinement effects. The only difference in analytical simulation, Beam Type-5 was as effective as Beam Type-3. This effectiveness of Beam Type-5 method was due to perfection of loading system in analytical simulation. Analytical simulation result were found to slightly underestimate in beams where strengthening is done with vertical stirrups only as compare to experimental result. But Beams strengthened with both vertical and horizontal stirrups were found to be consistent with the experiment. So horizontal leg of shear stirrups have a great role on shear resistance of a beam. In both programs, the horizontal plate was used to confine the concrete and as a result this confinement used the beam to resist high shear load. Based on simulation the effect of initial pre strain was found no effect on ultimate load of the beam.

Other researcher in the future can study about following point.

- Effectiveness of these techniques on deep beam and
- Effects of hole size on shear capacity

In coordination of the current and future research's a concrete idea or knowledge will be contribute about all type of beams on shear strengthening.

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## 7.2 Recommendation

1. To apply these strengthening methods in practical work usage, multiply their respective ratio ( $V_{s,exp} / V_{s,theo}$ , as expressed in **table 5.1**) with conventional web reinforcement design.
2. Horizontal plates (horizontal stirrups) used to tie the vertical stirrups should be very rigid, to use full capacity of vertical stirrups.
3. Drilled and grooved sections should fill with cementing material as much as possible to make good bond with existing structure.
4. Beam type-4 and 5 (provide vertical stirrups only) should not use in a place where torsion effect is considerable
5. During grooving and drilling of a structural elements care should be done to protect internal reinforcement from any damage.
6. Designer can choose configuration types depending on aesthetic value, strength wise, existing structure design condition, simplicity of construction, time wise and cost wise.
7. For practical design work, designer can use simulation software result for beams where strengthened with both vertical and horizontal web reinforcement.
8. In beams strengthening with vertical stirrups only, the head of vertical stirrups should be greater than drilled hole.

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## APPENDIX

### Procedures of concrete mixed design

Target of compressive strength =25MPa (C-25)

Sample – 1

- Materials parameters are described as follow.

Cement; type 1; specific gravity= 3.15

Bulk specific gravity C.A=2.61

Compacted unit weight C.A=1558.33 KN/m<sup>3</sup>

Bulk specific gravity F.A =2.51

Fines modulus F.A=2.60

➤ The mix design procedures are as follows:-

1.choice of slump

**Table 1: Recommended slumps for various types of construction.**

Types of construction	Maximum Slump (cm)	Minimum Slump (cm)
Reinforced foundation walls and footings	8	2
Plain footings, caissons, and substructure walls	8	2
Beams and reinforced walls	10	2
Building columns	10	2
Pavements and slabs	8	2
Mass concrete	8	2

Since the type construction is beam so from table 1, maximum slump= 10cm and minimum slump= 2cm.

2. maximum size of aggregates is 25 mm

3. Estimation of mixing water and air content

Assume the concrete is non air entrained

**Table 2: Approximate Mixing Water Requirements for Different Slumps and Maximum Sizes of Aggregates**

NON-AIR-ENTRAINED CONCRETE								
Slump (mm)	10 mm	12.5 mm	20 mm	25 mm	40 mm	50+ mm	70+ mm	150+ mm
3 to 5	205	200	185	180	160	155	145	125
8 to 10	225	215	200	195	175	170	160	140
15 to 18	240	230	210	205	185	180	170	-
Air entrapped (%)	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.2

For non-air entrained and slump of 8-10cm, the water in 1m<sup>3</sup> of concrete is 195Kg.

4. Water to cement ratio selection table 3

**Table 3: Relationship between water-cement compressive strength of concrete**

Compressive strength at 28 days (MPa)	Water-cement ratio by weight (Non-air-entrained concrete)
45	0.38
40	0.43
35	0.48
30	0.55
25	0.62
20	0.70
15	0.80

For C-25 and non-air entrained concrete water to cement ratio is 0.62.

5. Cement content calculation

For slump = 8-10cm

Water content=195Kg/m<sup>3</sup>

Water/cement=0.62

$$\begin{aligned}
 \text{cement content} &= \text{water content} / \left(\frac{w}{c}\right) \\
 &= \frac{195}{0.62}
 \end{aligned}$$

$$= 314.52 \text{ Kg/m}^3$$

6. Estimation of coarse aggregate quantity

**Table 4: Volume of dry-rodded coarse aggregate per unit volume of concrete for different fineness moduli of sand.**

Nominal maximum size of aggregate (mm)	2.40	2.60	2.80	3.00
10	0.50	0.48	0.46	0.44
12.5	0.59	0.57	0.55	0.53
20	0.66	0.64	0.62	0.60
25	0.71	0.69	0.67	0.65
40	0.76	0.74	0.72	0.70
50	0.78	0.76	0.74	0.72
70	0.81	0.79	0.77	0.75
150	0.87	0.85	0.83	0.81

The sand have 2.6 fineness modules and the maximum size of aggregate is 25mm

The volume of dry rodded coarse aggregate per unit volume of concrete is 0.69

Unit weight of C.A =  $1558.33 \text{ kg/m}^3$  from laboratory

$$\text{required dry mass of C.A in } 1 \text{ m}^3 = 0.69 * 1558.33$$

$$= 1075.25 \text{ kg/m}^3$$

7. Estimation of fine aggregates content

First estimate the unit weight of fresh concretes.

**Table 5: First estimate of concrete weight (kg/m<sup>3</sup>)**

Nominal maximum size of aggregate (mm)	Non-air-entrained concrete
10	2280
12.5	2315
20	2355
25	2375
40	2420
50	2445
70	2465
150	2505

The unit weight of fresh concrete for max. Aggregate size of 25mm and non- air entrained is  $2375 \text{ kg/m}^3$ .

Form the above

- Cement content = 314.52 kg/m<sup>3</sup>
- Water content = 195 kg/m<sup>3</sup>
- Coarse aggregate content = 1075.25 kg/m<sup>3</sup>
- Fresh concrete content = 2375 kg/m<sup>3</sup>

Fine aggregate can be quantify in two methods.

- ✓ weight method or
- ✓ absolute volume method

Weight method is used in this paper

➤ **Content of fine aggregate (F.A) = unit weight of concrete – (C.A + cement + water)**

Fine aggregate content =  $[2375 - (1075.25 + 314.52 + 195)] = \underline{\underline{790.23 \text{ kg/m}^3}}$

#### 8. Moisture adjustment

Absorbed water does not become part of the mixing water and it must be removed from the mixing water, if moisture content is greater than absorption capacity. But, if absorption capacity is greater than moisture content of aggregate, we need to add water up to its moisture capacity. Therefore, in this case since the moisture content of the aggregates are greater than their absorption capacity, water should be deducted from the mixing water.

Coarse aggregates:

- ✓ absorption capacity = 2.11 %
- ✓ moisture content = 2.05 %

Fine aggregate (sand)

- ✓ absorption capacity = 2.46 %
- ✓ moisture content = 2.81 %

Adjusted fine aggregate =  $790.23 * 1.0281 = 812.46 \text{ kg/m}^3$

Adjusted coarse aggregate =  $1075.25 * 1.0205 = 1097.29 \text{ kg/m}^3$

Adjusted water =  $195 - [1075.25 * (0.0205 - 0.0211) + 812.46 * (0.0281 - 0.0246)] = 192.84 \text{ kg/m}^3$

**Table 6: Estimated ingredients for a meter cube of concrete**

Ingredients	Weight per m <sup>3</sup> (kg/m <sup>3</sup> )	Ratio
Cement	314.52	1
Fine aggregate	812.46	2.58
coarse aggregate	1097.29	3.49
Water	192.84	0.61
Conc. Unit weight	<b>2417.11</b>	-

In this paper for one beam there are 6 cubes casted.

- Volume of a Beam Concrete =  $1.7 \times 0.2 \times 0.25 = 0.085 \text{m}^3$
- Cubes =  $6 \times 0.15 \times 0.15 \times 0.15 = 0.02025 \text{m}^3$

Total volume (wastage and shrinkage is 20 %) =  $0.1263 \text{m}^3$

**Table 7: Ingredients for one beam and 6 cubes**

Ingredients	Weight per m <sup>3</sup> (kg/m <sup>3</sup> )
Cement	39.75
Fine aggregate	102.56
coarse aggregate	138.73
Water	24.25

### Sample – 2

- Materials parameters are described as follow.

Cement; type 1; specific gravity= 3.15

Bulk specific gravity C.A=2.76

Compacted unit weight C.A=1630.23 KN/m<sup>3</sup>

Bulk specific gravity F.A =2.55

Fines modulus F.A=3.00

➤ The mix design procedures are as follows:-

1. choice of slump

**Table 8: Recommended slumps for various types of construction.**

Types of construction	Maximum Slump (cm)	Minimum Slump (cm)
Reinforced foundation walls and footings	8	2
Plain footings, caissons, and substructure walls	8	2
Beams and reinforced walls	10	2
Building columns	10	2
Pavements and slabs	8	2
Mass concrete	8	2

Since the type construction is beam so from table 1, maximum slump= 10cm and minimum slump= 2cm.

2. maximum size of aggregates is 37.5 mm
3. Estimation of mixing water and air content

Assume the concrete is non air entrained

**Table 9: Approximate Mixing Water Requirements for Different Slumps and Maximum Sizes of Aggregates**

NON-AIR-ENTRAINED CONCRETE								
Slump (mm)	10 mm	12.5 mm	20 mm	25 mm	40 mm	50+ mm	70+ mm	150+ mm
3 to 5	205	200	185	180	160	155	145	125
8 to 10	225	215	200	195	175	170	160	140
15 to 18	240	230	210	205	185	180	170	-
Air entrapped (%)	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.2

For non-air entrained and slump of 8-10cm, the water in 1m<sup>3</sup> of concrete by interpolation is 178.34 Kg.

4. Water to cement ratio selection table 3

**Table 10: Relationship between water-cement compressive strength of concrete**

Compressive strength (MPa)	at 28 days	Water-cement ratio (Non-air-entrained concrete)	by weight
45		0.38	
40		0.43	
35		0.48	
30		0.55	
25		0.62	
20		0.70	
15		0.80	

For C-25 and non-air entrained concrete water to cement ratio is 0.62.

#### 5. Cement content calculation

For slump = 8-10cm

Water content=178.34 Kg/m<sup>3</sup>

Water/cement=0.62

$$\begin{aligned}
 \text{cement content} &= \text{water content} / \left(\frac{w}{c}\right) \\
 &= \frac{178.34}{0.62} \\
 &= \underline{\underline{287.65 \text{ Kg/m}^3}}
 \end{aligned}$$

#### 6. Estimation of coarse aggregates quantity

**Table 11: Volume of dry-rodded coarse aggregate per unit volume of concrete for different fineness moduli of sand.**

Nominal maximum size of aggregate (mm)	2.40	2.60	2.80	3.00
10	0.50	0.48	0.46	0.44
12.5	0.59	0.57	0.55	0.53
20	0.66	0.64	0.62	0.60
25	0.71	0.69	0.67	0.65
40	0.76	0.74	0.72	0.70
50	0.78	0.76	0.74	0.72
70	0.81	0.79	0.77	0.75
150	0.87	0.85	0.83	0.81

The sand have 3.00 fines modules and the maximum size of aggregate is 37.5 mm

The volume of dry rodded coarse aggregate per unit volume of concrete by interpolation is 0.692

Unit weight of C.A =  $1630.23 \text{ kg/m}^3$  from laboratory

$$\begin{aligned} \text{required dry mass of C.A in } 1 \text{ m}^3 &= 0.692 * 1558.33 \\ &= \underline{\underline{1128.12 \text{ kg/m}^3}} \end{aligned}$$

#### 7. Estimation of fine aggregates content

First estimate the unit weight of fresh concretes.

**Table 12: First estimate of concrete weight (kg/m<sup>3</sup>)**

Nominal maximum size of aggregate (mm)	Non-air-entrained concrete
10	2280
12.5	2315
20	2355
25	2375
40	2420
50	2445
70	2465
150	2505

The unit weight of fresh concrete for max. Aggregate size of 37.5mm and non- air entrained is **2412.5 kg/m<sup>3</sup>**.

Form the above

- Cement content =  $287.65 \text{ kg/m}^3$
- Water content =  $178.34 \text{ kg/m}^3$
- Coarse aggregate content =  $1128.12 \text{ kg/m}^3$
- Fresh concrete content =  $2412.5 \text{ kg/m}^3$

Fine aggregate can be quantify in two methods.

✓ weight method or

✓ absolute volume method

Weight method is used in this paper

➤ **Content of fine aggregate (F.A) = unit weight of concrete – (C.A + cement + water)**

Fine aggregate content =  $[2412.5 - (1128.12 + 287.65 + 178.34)] = \underline{\underline{818.40 \text{ kg/m}^3}}$

8. Moisture adjustment

Absorbed water does not become part of the mixing water and it must be removed from the mixing water, if moisture content is greater than absorption capacity. But, if absorption capacity is greater than moisture content of aggregate, we need to add water up to its moisture capacity. Therefore, in this case since the moisture content of the aggregates are greater than their absorption capacity, water should be deducted from the mixing water.

Coarse aggregates:

✓ absorption capacity = 1.16 %

✓ moisture content = 1.84 %

Fine aggregate (sand)

✓ absorption capacity = 2.25 %

✓ moisture content = 4.57%

Adjusted fine aggregate =  $818.40 * 1.0457 = 855.78 \text{ kg/m}^3$

Adjusted coarse aggregate =  $1128.12 * 1.0184 = 1148.83 \text{ kg/m}^3$

Adjusted water =  $178.34 - [1148.83 * (0.0184 - 0.0116)] + 855.78(0.0457 - 0.0225) = 151.72 \text{ kg/m}^3$

**Table 13: Estimated ingredients for a meter cube of concrete**

Ingredients	Weight per m <sup>3</sup> (kg/m <sup>3</sup> )	Ratio
Cement	287.65	1
Fine aggregate	855.78	2.98
coarse aggregate	1148.83	3.99
Water	151.72	0.53
Conc. Unit weight	<b>2417.11</b>	-

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In this paper for one beam there are 6 cubes casted.

- Volume of a Beam Concrete =  $1.7*0.2*0.25 = 0.085\text{m}^3$
- Cubes =  $6*0.15*0.15*0.15=0.02025 \text{ m}^3$

Total volume (wastage and shrinkage is 20 %) =  $0.1263\text{m}^3$

**Table 14: Ingredients for one beam and 6 cubes**

Ingredients	Weight per m <sup>3</sup> (kg/m <sup>3</sup> )
Cement	30.62
Fine aggregate	90.18
coarse aggregate	120.75
Water	16.04

## Design of beam

Dimension of beam and other specifications

- Total beam length = 1.7m
- Clear span of beam = 1.3m
- Depth of beam = 250mm
- Width of beam = 200mm
- Concrete cover = 25mm
- Stirrups diameter = 6mm (out of shear span to prevent bond failure)
- Longitudinal bar in one row (bottom) = 20mm (two number of bars)
- Longitudinal bar in one row (top) = 10mm (two number of bars)

### Initial data's and Material strength

$$d' = cc + \emptyset s + \frac{\emptyset L}{2} = 25 + 6 + \frac{20}{2} = 41mm$$

$$d = D - d' = 250 - 41 = 209mm$$

$$d_2 = cc + \emptyset s + \frac{\emptyset L}{2} = 25 + 6 + \frac{10}{2} = 36mm$$

Ratio of shear span to effective depth =  $\frac{av}{d} = \frac{0.65}{0.209} = 3.11$  is a slender beam

Actual **As** (longitudinal tension bars) = 549.3 mm<sup>2</sup> (2∅20)

Actual **As2** (longitudinal compression bars) = 139.39 mm<sup>2</sup> (2∅10)

Concrete

Rebar

C-25/20

$f_{y\text{long.tension}} = 640.48\text{MPa}$   $f_{yw} = 587.39\text{MPa}$

$f'_{cm} = 28\text{MPa}$

$f_{y\text{long.compression}} = 520\text{MPa}$

$K_2 = 1.6 - d = 1.6 - 0.209 = 1.39$

$f_{ct} = 2.2\text{MPa}$  from new design code

$$K_1 = 1 + 50 * \rho = 1.66$$

$$V_c = 0.25 * f_{ct} * k_1 * k_2 * b * d = 53.0 \text{ KN}$$

Back analysis of beam by using the actual specification of materials the maximum moment capacity of the beam

$$M_{d,s} = 62.51 \text{ KNm}$$

$$M = \frac{PL}{4} \quad P = \frac{4M}{L} = \frac{4*62.51}{1.3} = 192.34 \text{ KN}$$

$$\text{Shear strengthening by percent (\%)} = \frac{P}{2*V_c} * 100 = 181.45 \%$$

Compute  $\gamma_{u,s} = \frac{Mu,s}{f_c * b * d^2}$  &  $K_x, \max = 0.8(\delta - 0.44)$ , where  $\delta = 1$  for 0% moment redistribution.

$$\gamma_{u,s}^* = 0.295 \text{ for } 0\%$$

$$\gamma_{u,s} = \frac{Mu,s}{f_c * b * d^2} = 0.256 < 0.295$$

If  $\gamma_{u,s} < \gamma_{u,s}^*$ , then the section is singly reinforced and  $A_s$ :

$$K_z = 0.85 \quad Z = K_z * d = 0.79 * 209 = 177.6 \text{ mm}$$

$$A_s = \frac{Mu,s^*}{Z * f_y} = 549.12 \text{ mm}^2$$

$$K_x = \frac{(A_s) * m}{bd} = 0.376 < 0.488 \text{ ok reinforcement at bottom first yield}$$

Anchorage length

$$f_b = 2 f_{ct} \quad - \text{ Deformed bar.}$$

$$l_b = \frac{\emptyset * f_y}{4 * f_b} = 1032.30 \text{ mm}$$

$$l_{b \text{ net}} = a l_b * \frac{A_{s \text{ cal}}}{A_{s \text{ prov}}} = 722.61 \text{ mm}$$

Shear reinforcement design

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$$A_{s \text{ shear}} = 19.63 \text{ mm}^2 \quad A_v = 2 * A_{s \text{ shear}} \quad \text{spacing} = 130 \text{ mm}$$

$$V_s = \frac{A_v * d * f_y}{S} = \frac{39.27 * 209 * 587.39}{130} = 37.1 \text{ kN}$$

$$V_c = 53.0 \text{ kN} \quad V_s = 37.1 \text{ kN}$$

$$\% = \frac{53 - 37.1}{37.1} * 100 = 42.86\%$$

Strengthening the shear by 142.86%

$$\text{Total load of shear force} = 2 * (53.0 + 37.1) = 180.2 \text{ kN}$$

Total load of bending = 192.34 kN > 180.2 kN Fail in shear