CRITICAL STUDY OF SHEAR CAPACITY OF REINFORCED CONCRETE BEAM HAVING FRP REINFORCEMENT

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by

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Synopsis

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1. Abstract

Sustainable structures are the need of today where the root cause of deterioration of the structures is corrosion of steel reinforcement. Different forms of FRPs have proved to be a good alternative to the conventional steel reinforcement because of the properties like high tensile strength, noncorrosive, nonmagnetic and light weight. Extensive research is ongoing worldwide and design recommendations are produced by various standards; even though, there are many challenges for using FRPs as primary reinforcement. This study is concentrated on shear capacity of RC elements using FRP reinforcement, specifically shear contribution made by shear reinforcement. Various design standards adopt different approaches to predict shear contribution made by the stirrups by keeping permissible strain limit or bend strength as upper limit. The range of permissible strain in FRPs is from 0.0025 to 0.004 in different standards (i.e. ISIS Canada, JSCE and ACI) which are very close to strain limit of steel reinforcement. Marginal difference between theoretical predictions and experimental results in the literature motivated to investigate the shear capacity of the beams with FRP reinforcement in flexure as well as shear. Advance testing on thirteen RC beams of size 230 x 300 x 2000 mm with GFRP as flexural and shear reinforcement is done by data observation of stain development at critical locations as well as deflection at midspan. Different strain gauges like PL-90-11-3L for concrete (surface), BFLA-5-5-3L for composite reinforcement (GFRP) and FLA-3-11-1L for steel made by TML, Japan are used for strain measurement. Multi channel data acquisition system TMR-200 is used for data recording, where the midspan displacement is observed by displacement transducers CDP – 100. Perfect beam action was observed as well as all the type of shear failure like diagonal tension, shear compression, shear tension and stirrup failure were observed depending on the reinforcement and loading configuration. It is observed that average ultimate strains as well as at 0.5 mm crack width are considerably higher than the permissible limits prescribed in above mentioned standards. Hence, the study concluded with recommendation to increase permissible

strain limit of shear reinforcement specified by ISIS Canada, JSCE and ACI to improve the efficiency of the design recommendations.

2. Brief Description on the State of Art of Research Topic

Service life of the structures has remained a great concern for the growing as well as the stable economy. Major cause of deterioration of the structure is the corrosion of steel due to severe environmental conditions, which results into the reduced life of the structures. Due to non-corrosive nature, different forms of FRPs have gained the acceptance as an alternative to the steel reinforcement. However, brittle elastic behavior; low modulus of elasticity; bend strength and bond characteristics make the FRPs different from steel reinforcement [1 to 3]. Number of guidelines [4 to 10] and standards are produced for the safe design using FRP reinforcement worldwide. Almost all the recommendations are following same format $V_r = V_c + V_s$, where total shear capacity (V_r) is the individual contribution of concrete (V_c) and stirrups (V_s). However, all the standards have adopted different approaches to derive individual contributions, which provide conservative results in overall. Variety of experimentation have been done on the FRP-reinforced (FRP-RC) beams without shear reinforcement to evaluate V_c [13 to 25], whereas limited experimentation is done to evaluate V_s on FRP-RC beams.

To quantify stirrups contribution V_s similar relationship in FRP-RC elements is used as for steel reinforced concrete elements just by changing the stress level at failure in majority country's recommendations. Different recommendations provide limiting strain value for the FRP stirrups to avoid stirrup rupture in bent portion and to control crack width in the shear zone. From the literature, it is found that the tensile strength and stiffness of FRP stirrups are lesser than the straight element because of manufacturing of FRPs [26 to 29]. Bend strength is also governed by manufacturing process, bend radius, bar diameter and type of reinforcing bar [29].

Thus, this critical study is aimed to observe the effect of FRP reinforcement that affect on the shear capacity of the beam and derive related recommendations to improve the efficiency of design recommendations by experimental justification.

3. Objectives and Scope of Work

The research work focuses on, experimental investigation of RC beams having FRP reinforcement in shear as well as in flexure and to improve the shear capacity considering FRP as an alternative to the steel reinforcement for sustainable structures.

3.1 Objective of work

The objective of the work is to investigate the shear behavior of beams with FRP reinforcement experimentally to reduce the gap between theoretical predication and experimental behavior.

3.2 Scope of work

The scope of the study involves the following stages by having full scale testing of real size beams.

- Review of current design standards (ISIS Canada, JSCE and ACI) related to shear contribution made by concrete and FRP reinforcement.
- To perform parametric investigation to determine the most influencing parameters in shear contribution. It helps to decide the sample size which covers whole range of shear failure.
- To finalize the experimental program for materials to be used and cross verification of their properties as well as to define testing procedure and advanced instrumentation for the observation of experimental data.
- Data analysis and result interpretation to derive some conclusions compatible with the objective of the study.

4. Original Contribution by the Thesis

Researchers envisage that FRP is a future alternative to the steel as a primary reinforcement in concrete members considering advantageous characteristics. Substantial research has been going on to improve the performance and efficiency in FRP reinforced concrete members. Shear performance of the FRP reinforced concrete members requires greater input from the researcher to understand it well. Through the continuous efforts of the researchers, design recommendations for FRPs have been updated continuously; however, this area requires more concentration of the researchers to improve the efficiency. The objective of this research is to understand the shear performance of GFRP reinforced concrete members through advanced testing. Strain (indirectly stress) development in the GFRP shear and flexural reinforcement up to ultimate failure have been investigated and presented in this study.

5. Research Methodology

For achieving objectives of the research, parametric study, design of elements, experimental work, analytical study and behavioral study is done. Research methodology consists of review of various design recommendations like Canadian, Japanese and American standards. Parametric study of the beam reinforced with FRP reinforcement is made to determine most influencing parameters which affects on shear capacity. Analytical study of beams experimented with GFRP reinforcement with variations in loading positions and reinforcement detailing is done. Behavioral study is made in terms of crack development and bond characteristic at ultimate stage to check feasibilty of FRP as an alternative to steel reinforcement. A parametric formulation is derived for shear capacity of beam with FRP reinforcement.

5.1 Research Hypothesis

Literature has shown that analytical and experimental results are not matching for the shear capacity of the FRP RC beams. Strain limit for FRP reinforcement specified by various standards are close to the steel reinforcement. If strain limit is changed as per the behavior and property of FRP reinforcement, gap of the analytical and experimental results can be reduced. Hence, following is hypothesis of the study.

"The range of permissible strain limit in various design standards is from 0.025 to 0.004 which is after stage wise modification from 0.002 specifically used for steel reinforcement. The range of actual strain at ultimate stage is from 0.012 to 0.03, which is considerably higher than the permissible. If permissible strain limit is increased depending on experimental behavior, effective utilization of the FRP reinforcement can be increased which leads to economical design."

5.2 Review of the Shear Design Recommendations

Traditionally, shear capacity of the reinforced concrete elements is evaluated as the addition of concrete and stirrups contributions with steel reinforcement; similarly it is followed for FRP reinforcement also. Majority of the design recommendations produced for FRP applications, conceptually replaces the steel reinforcement by FRPs with due modifications considering fundamental differences of the properties between them. Permissible stain approach in FRP stirrups is advisable to maintain the harmony and to control the shear crack width. This also helps to avoid failure of the FRP stirrups in the bent portion due to limited stress development (ACI 2006). The shear strength contribution for concrete (V_c) and FRP reinforcement (V_{FRP}) as specified by the ISIS Canada (2007), JSCE (1997) and ACI (2006) reviewed are as follows:

$$V_r = V_c + V_{FRP} \tag{1}$$

5.2.1 ISIS Canada Design Manual (2007)

$$V_c = 0.2\lambda\Phi_c\sqrt{f'_c}b_w d\sqrt{\frac{E_{frp}}{E_s}} \text{ where, } \sqrt{\frac{E_{frp}}{E_s}} \leq 1 \tag{2}$$

For the sections with an effective depth greater than 300 mm and not containing at least minimum transverse reinforcement the concrete resistance, Vc, is taken as,

$$V_c = \left(\frac{260}{1000+d}\right)\lambda\varphi_c\sqrt{f'_c}b_w d\sqrt{\frac{E_{frp}}{E_s}} \text{ where, } \sqrt{\frac{E_{frp}}{E_s}} \leq 1 \tag{3}$$

$$V_{FRP} = \varphi_{frp}\frac{A_{fv}\,\sigma_v d_v \cot\theta}{s} \tag{4}$$

$$\sigma_v = \frac{\left(0.05\frac{r_b}{d_b} + 0.3\right)f_{frpv}}{1.5} \tag{5}$$

$$\sigma_v = E_{frpb}\varepsilon_v \tag{6}$$

$$\varepsilon_{fv} = 0.0001\sqrt{f'_c\frac{\rho_{frp}E_{frp}}{\rho_{frpv}E_{frpv}}}\left[1 + 2\left(\frac{\sigma_N}{f'_c}\right)\right] \leq \mathbf{0.0025} \tag{7}$$

5.2.2 JSCE (1997) Recommendations

The shear contribution of concrete as recommended is obtained as

$$V_c = \beta_d\beta_p\beta_n f_{cvd}\, bd / \gamma_b \tag{8}$$

$$f_{cvd} = 0.2(f'c)^{1/3} \leq 0.72\, N/mm^2 \tag{9}$$

$$\beta_d = (1000/d)^{1/4} \leq 1.5 \tag{10}$$

$$\beta_p = (100\,\rho_{fl}E_{fl}/E_s)^{1/3} \leq 1.5 \tag{11}$$

$$\beta_n = 1 + \frac{M_o}{M_d}, \ if\ \beta_n > 2 \ or\ N_f \geq 0 \quad (12)$$

$$\beta_n = 1 + \frac{2\ M_o}{M_d}, \ if \beta_n < 0 \ or\ N_f < 0 \quad (13)$$

The shear contribution by FRP stirrups is calculated as

$$V_{FRP} = [A_{fv}\ E_{fv}\ \varepsilon_{fv}\ (\sin\alpha s + \cos\alpha s)\ /\ s]\ z\ /\ \gamma_b \quad (14)$$

$$\varepsilon_{fv} = 0.0001\sqrt{f'_{mcd}\frac{\rho_{fl}E_{fl}}{\rho_{fv}E_{fv}}}\left[1 + 2\left(\frac{\sigma_N}{f'_{mcd}}\right)\right] \leq \boldsymbol{f_{FRPbend}}\ /\ \boldsymbol{E_{fv}} \quad (15)$$

$$f_{FRPbend} = \left(0.05\frac{r_b}{d_b} + 0.3\right)f_{fuv}\ /\ \gamma_{mfb} \quad (16)$$

$$f'_{mcd} = \left(\frac{h}{300}\right)^{-1/10} f'_{cd} \quad (17)$$

$$\sigma_N = N_f\ /\ A_g \leq 0.4\, f'_{mcd} \quad (18)$$

5.2.3 ACI 440.1R-06 (ACI 2006)

The shear resistance of concrete V_c in FRP-RC element specified by the ACI 440.1R-06 (ACI 2006) is as follows

$$V_c = \frac{2}{5}\sqrt{f'_c}b_w c \quad (19)$$

$$c = kd \quad (20)$$

$$k = \sqrt{2\ \sigma_f n_f + (\sigma_f n_f)^2} - \sigma_f n_f \quad (21)$$

The shear resistance of FRP stirrups V_{FRP} of the member is calculated as

$$V_{FRP} = \frac{A_{fv}\sigma_{fv}d}{s} \quad (22)$$

$$\sigma_{fv} = \mathbf{0.004}E_{fv} \leq f_{FRPbend} \quad (23)$$

$$f_{FRPbend} = \left(0.05\frac{r_b}{d_b} + 0.3\right)f_{FRPu}\ /\ 1.5 \leq f_{FRPu} \quad (24)$$

5.3 Parametric Study

For the finalization of sample size and variation in the sample to explore the shear behavior in different situation ACI 440.1R-06 (ACI 2006) is considered. A parametric study is carried out to check the most influencing parameters in overall behavior of shear failure. An excel program is developed using suggested method in ACI. Effect of tensile strength of GFRP bars, modulus of elasticity, stirrups diameter, bend radius of stirrups, FRP reinforcement ratio and span/depth ratio have been observed parametrically. The parameters are varied like tensile strength of reinforcement (415 MPa to 750 MPa), stirrups diameter (6mm to 12mm), bend radius of stirrups (3 to 6 r_b), FRP reinforcement ratio (0.009 to 0.016), modulus of elasticity (44.8 GPa to 60 GPa) and span/depth ratio (1.79 to 2.69).

5.4 Result of Parametric Study

Parametric study concluds that the span/depth ratio, spacing of stirrups and modulus of elasticity of FRP reinforcment are the major influencing factors in overall shear capacity of the beam.

5.5 Experimentation

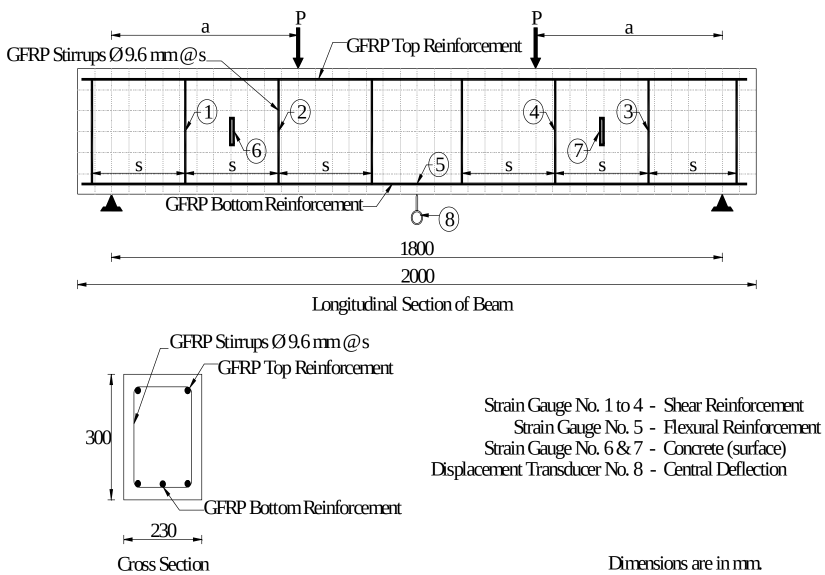


Fig.1 Typical Cross Sectional Details of Beam.

Based on the parametric study, experimentation is done of RC beams with FRP reinforcement with variation in most influencing parameters which affect on shear capacity. Total thirteen real size beams are casted and investigated in this experimental study as per typical cross sectional details of the beam shown in Fig.1. Out of thirteen beams, one is reinforced with steel while other twelve beams are reinforced with GFRP with longitudinal and shear reinforcement. The beams with dimensional parameters of 230 mm wide, 300 mm depth and total length of 2000 mm including 100 mm overhanging on each end are considered in the investigation. Total six combinations are taken by keeping variation in shear span to depth ratio and spacing of shear reinforcement with the aim to have different possible variation in shear behavior and ultimate strain condition in stirrups. Variation in modulus of elasticity is not considered as Dextra India Pvt. Ltd. is manufacturing the GFRP bars with single grade of modulus of elasticity that is 40.8 GPa. The Details of the flexural and shear reinforcement derived using standard ACI-440.1R-06 are presented in Table 1.

Table 1. Details of the flexural and shear reinforcement

Beam[a]	a (mm)	a/d	Top Bars	Bottom Bars	Stirrups Dia. (mm)	S (mm)
SB.2.1	650	2.33	2-#10	3-#16	#8	275
GA.1.1 GA.1.2	500	1.79	2-Φ9.5	2-Φ18.71 + 1-Φ15.25	Φ9.5	250
GA.2.1 GA.2.2	500	1.79	2-Φ9.5	2-Φ18.71 + 1-Φ15.25	Φ9.5	275
GB.2.1 GB.2.2	650	2.33	2-Φ9.5	2-Φ18.71 + 1-Φ15.25	Φ9.5	275
GB.3.1 GB.3.2	650	2.33	2-Φ9.5	2-Φ18.71 + 1-Φ15.25	Φ9.5	300
GC.4.1 GC.4.2	750	2.69	2-Φ9.5	3-Φ18.71	Φ9.5	325
GC.5.1 GC.5.2	750	2.69	2-Φ9.5	3-Φ18.71	Φ9.5	350

[a]G$.%.N: G Type of Longitudinal and shear reinforcement (S : Steel and G : GFRP); $ denotes distance "a", the location of two point load as per fig. 1 (A = 500mm, B = 650mm, and C = 750mm); % denotes spacing of shear reinforcement (1 = 250mm, 2 = 275mm, 3 = 300mm, 4 = 325mm and 5 = 350mm), N denotes serial number of the beam of that type. # denotes tor steel reinforcement and Φ denotes GFRP reinforcement

5.5.1 Materials

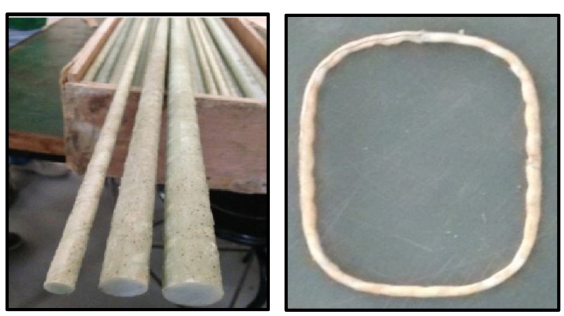


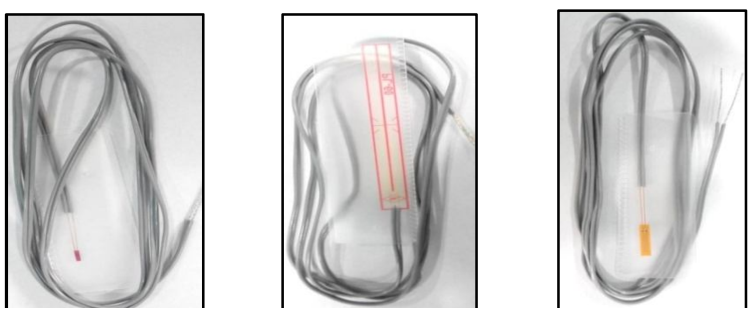
Fig.2 GFRP bars stirrups and strain gauges.

All the specimens are casted in the Material Testing Laboratory of Marwadi Education Foundation's Group of Institutions, Gujarat, India using ready mixed concrete with a target compressive strength of 30 MPa at 28-days supplied by the Lafarge India Pvt. Ltd. Where the GFRP reinforcement made of continuous longitudinal glass fibers impregnated in a thermosetting vinyl ester resin using infusion process with a average fiber content of 81.87% (by weight), manufactured by Dextra Group, are used as longitudinal and shear reinforcement as shown in Fig.2. Table 2 contains the properties of concrete and GFRP reinforcement of test specimens.

Table 2. Properties of concrete and GFRP reinforcement

Concrete		GFRP Reinforcement					
$f'c$ (Mpa)	E_c (Gpa)	d_b (mm)	Barcol Hardness	Fibre Content (%)	f'_{frpu} (Mpa)	E_{frp} (Gpa)	Ultimate Strain
34.65	22.04	9.5	60	82.72	871	48.3	1.93
		15.25	62	82.64	904	48.2	2.05
		18.71	56	80.26	955	47.3	2.16

5.5.2 Instrumentation



3a. FLA – 3- 11- 1L 3b. PL-90-11-3L 3c. BFLA-5-5-3L

Fig. 3 Types of strain gauges

To observe strain on the reinforcement and concrete, strain gauges manufactured by Tokyo Sokki Kenkyujo Co. Ltd. (TML), Japan are used. Specific strain gauges like PL-90-11-3L for concrete (surface), BFLA-5-5-3L for composite reinforcement (GFRP) and FLA – 3- 11- 1L for steel are used to observe the strain as shown in Fig.3. The mid-span deflection of the beam is measured using displacement transducers CDP – 100 (TML). Data observation of strain gauges and central deflection is made through data acquisition system TMR-200 from Tokyo Sokki Kenkyujo Co, Ltd. from eight locations as shown in Fig.1. TMR-200 can capture the data at high speed of 100kHz with time step of 0.01 to 20000ms and sensor input units include not only analog input/output for strain, voltage, temperature, etc. but also digital input/output unit for CAN, etc. up to 80 channels. All the beams are tested in four-point bending over a simply supported clear span of 1,800 mm in loading frame of capacity 550 kN. The complete test setup is shown in Fig. 4.

Fig. 4 Test setup

5.6 Results and Discussions

The summary of the test results regarding the shear capacity of test specimens like their capacity & mode of failure, result interpretation and comparison are introduced through this section.

5.6.1 Capacity and Mode of Failure

As per the research objective all the test specimens reinforced with steel and GFRP reinforcement were designed to fail in shear. Hence, the ultimate failure of the entire test specimen was governed by the stirrup contribution. Major difference in load level was observed as per a/d ratio while spacing of stirrups made marginal difference. All the beams failed with similar mechanism; however, the load levels of different categories were different. Sudden failure occurred due to diagonal tension cracks and rupture of GFRP stirrups. GFRP stirrups ruptured at the bend initially; subsequently, beams failed as other shear resisting mechanisms could not resist the shear force applied. This was because the flexural strength provided was greater than the shear strength of the beams. Crack patterns of the failed beams are shown in Fig. 5. The test specimens showed similar cracking pattern and inclination angle. However, the difference was in the total number of diagonal cracks appeared in the shear span and consequently their spacing. The higher the failure load the higher the number of shear cracks.

GA.1.1

GA.1.2

GA.2.1

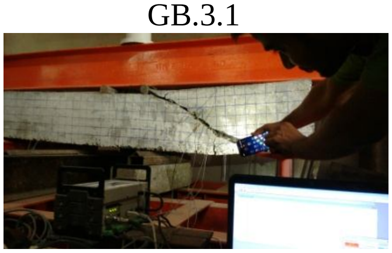
GA.2.2

GB.2.1

GB.2.2

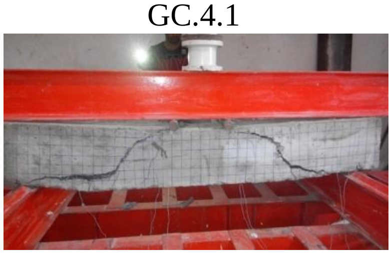
GB.3.1

GB.3.2



GC.4.1

GC.4.2



GC.5.2

GC.5.2

Fig. 5 Failure of Test Specimens

5.6.2 Result Interpretation

All the thirteen beam specimens including one steel reinforced failed in shear prior to reaching their flexural capacity. Hence, brittle failure was observed in all the beams. Data Observed through eight locations as per Fig.1 are interpreted with shear force to study the behavior and derive the conclusions. Midspan deflection, concrete crack width, flexural strain on longitudinal reinforcement, concrete surface strain and stirrup strain are interpreted with shear force and the relationships are shown in Fig. 6 to 10 respectively.

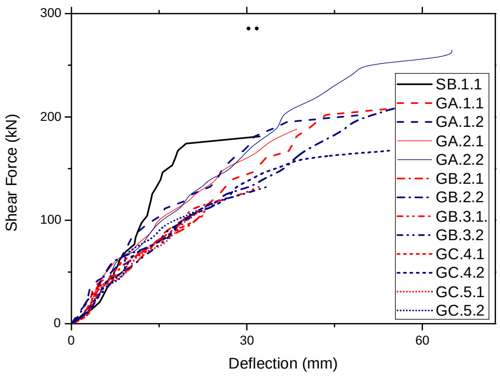


Fig. 6 Shear Force – Midspan Deflection relationship of all beam specimens.

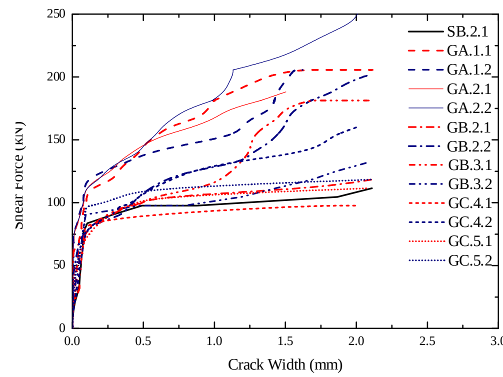


Fig. 7 Shear Force – Crack Width relationship of all beam specimens.

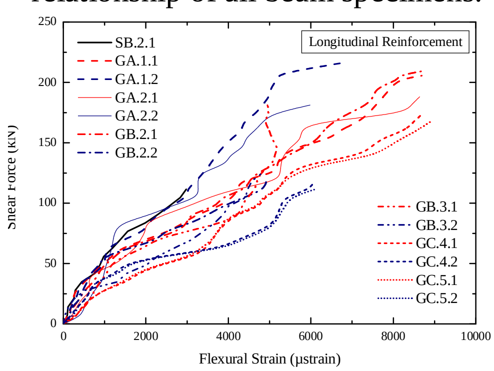


Fig. 8 Shear Force – Flexural Strain on Longitudinal R/F Relationship at Midspan.

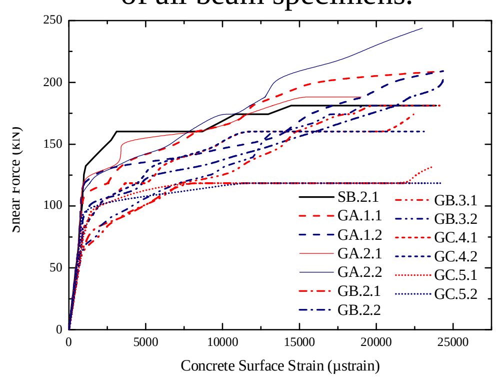


Fig. 9 Shear Force – Concrete Surface Strain Relationship of All Beam Specimens.

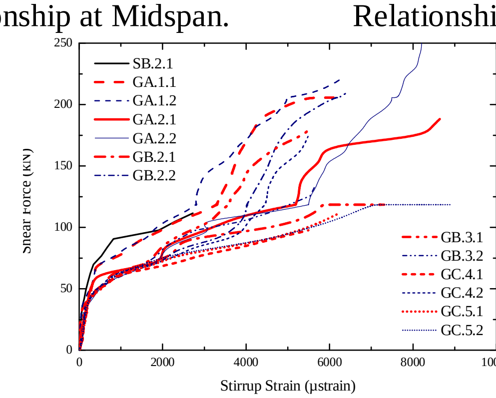


Fig. 10 Shear Force – Stirrup Strain Relationship of All Beam Specimens.

The testing was done with controlled rate of loading. Strain gauges are applied on both the shear zone as per Fig. 1. In general, the stirrups strains remained very small until diagonal cracks were developed; then, rapid increase in the strain was observed until failure. Details relevant to shear failure like shear crack load, ultimate shear, shear crack angle, maximum stirrup strain and type of failure are represented in Table 3.

Table 3. Shear Prediction, Performance and Failure of GFRP Reinforcement

Beam	Shear Crack Load V_{cr} (kN)	Ultimate Shear V_{Exp} (kN)	Angle of Major Crack, θ (Degree)	Maximum Stirrups Strain (μstrain)	Mode of Failure[a]	V_{Exp}/V_{Pred}		
						ISIS 2007	JSCE 1997	ACI 2006
SB.2.1	40.08	55.76	45	2726	ST	--	--	--
GA.1.1	54.02	102.81	49	6189	DT	2.72	2.23	1.86
GA.1.2	59.25	111.52	49	8642	DT	2.57	2.11	1.76
GA.2.1	54.02	94.10	46	6363	SR	2.84	2.30	2.00
GA.2.2	55.76	130.69	47	8204	DT	2.85	2.30	2.00
GB.2.1	34.85	59.25	46	6386	SC	1.96	1.58	1.38
GB.2.2	38.34	104.55	49	7312	SC	2.17	1.76	1.53
GB.3.1	34.85	90.61	47	5578	SC	2.00	1.60	1.44
GB.3.2	45.31	66.22	45	5634	SR	1.93	1.54	1.39
GC.4.1	45.31	49.49	39	5499	ST	1.94	1.49	1.41
GC.4.2	38.34	66.22	42	5488	ST	2.14	1.64	1.55
GC.5.1	34.85	55.76	45	6228	ST	2.16	1.65	1.59
GC.5.2	48.79	59.25	45	8936	ST	2.18	1.66	1.61
					Average	2.29	1.82	1.63
					SD	0.36	0.31	0.23

[a]ST = Shear Tension, DT = Diagonal Tension, SR = Stirrups Rupture and SC = Shear Compression.

5.6.3 Comparison of Experimental and Predicted Shear Strength

Table 3 also presents a comparison between the experimentally measured shear capacity and the predicted ones. It can be observed from the Table 3 that shear provisions in both the standards ISIS Canada (2007) and JSCE (1997) greatly underestimate the shear strength while ACI (2006) predicts reasonable capacity which is yet conservative. This is referred to the common concept in calculating the concrete contribution (V_c) and FRP stirrup contribution (V_{FRP}) separately to derive shear capacity of the beam.

6. Achievements with respect to Objectives

In the research conducted, following work is done with respect to objectives.

1. Comparative analysis is made for the shear capacity of the beams having FRP reinforcement in flexure and shear prescribed by various standards to study the factors influencing for prediction of shear capacity and compared with experimental performance.
2. Parametric studies are made to observe most influencing parameter on overall shear capacity of the beam so that it would guide in preparation of range of the parameters to be adopted in sample size for the final experimentation of the study.
3. Experiments are conducted on thirteen beams including one with steel reinforcement to derive the strain limit and suggest modification in design recommendation for taking maximum benefit of estimating shear capacity of beam reinforced with GFRP reinforcement.

7. Summary

The research work aims to see the FRPs as an alternate option to the conventional steel reinforcement. It emphasis on the theoretical predictions as well as experimental behaviour of the beams specifically in shear and having FRP reinforcement in flexure as well as in shear. Current design standards have developed the design recommendations by just replacing steel parameters by the FRP parameters. Where, both the materials steel and FRP do have different characteristics fundamentally. Hence, an effort is made through this study to determine the strain limit which may lead to more efficient design recommendations.

The experimental investigation shows that there is no issue about using FRP as an internal reinforcement. All the different types of failure like shear tension, diagonal tension, shear compression or stirrups failure are observed in the study as it happened to be with steel reinforcement. Permissible strain approach is adopted in majority of the design standards which is a controlling parameter for predicting the stirrup contribution. Hence, with the objective as defined, experimentation is designed in such a way that all the possibilities of shear failure are covered and determining the actual strain development in the stirrups. Advance experimentation is conducted by placing strain gauges at different locations on longitudinal and lateral (shear) reinforcement before casting and strain gauges on concrete are applied after casting at the time of

testing in shear zone. Experimental results suggest the increase in permissible strain in FRP stirrups.

8. Conclusions

The experimental behavior and shear strength obtained through the advanced testing of the beams reinforced with GFRP longitudinal and lateral reinforcement are presented and discussed. The main variables were shear span to depth ratio and spacing of the shear reinforcement (stirrup). Sand-coated GFRP stirrups of 9.5 mm diameter were used as shear reinforcement with different spacing. The experimental test results were compared to the shear design provisions provided by ISIS Canada (2007), JSCE (1997) and ACI (2006). The main findings of this investigation can be summarized as follows:

1. In the FRP-RC beams, GFRP stirrups as shear reinforcement did not affect the failure mechanism as a beam action in all the beams. Initial hair crack in flexure and subsequently shear failure happened in all the beams.
2. Strain development started at the initial stage of loading in case of higher spacing of stirrups compare to lower spacing. However, spacing did not affect the ultimate strain developed in the stirrups.
3. With the collective effect of shear span to depth ratio, cross section of beam, amount of shear and anchorage reinforcement majority diagonal tension, shear compression and shear tension was observed for the shear span to depth ratio 1.79, 2.33 and 2.69 respectively.
4. The average maximum strain in GFRP stirrup observed was 6705 microstrains with a maximum strain of 8936 microstrains in the cases where stirrups failure occurred. The average strain observed in the stirrups at 0.5 mm crack width is 4712 microstrain which is higher than the limits specified in ISIS Canada, JSCE and ACI.
5. Crack angle of the failed specimens varied from 39° to 49° with an average of around 45°, which shows good agreement with traditional truss model.
6. Shear capacity predicted by ISIS Canada (2007) is the most conservative with the ratio V_{Exp}/V_{Pred} as 2.29 out of three. Both the contributions concrete and shear are underestimated by this standard. There is no point in calculating concrete contribution by considering steel as the reference material. Permissible strain value 0.0025 is also very low compare to actual values as well as 0.004 as used by ACI (2006).

7. JSCE (1997) also gives the conservative prediction with the ratio V_{Exp}/V_{Pred} as 1.82. Keeping the bend strength as upper limit is reasonable but Eq. (15) underestimates the strain value to be considered.
8. ACI (2006) have shown good agreement with the ratio V_{Exp}/V_{Pred} as 1.63 which is yet conservative. Initially ACI-440.1R-03 had proposed permissible strain value as 0.002 similar to the steel reinforcement. This has been revised in ACI-440.1R-06 as 0.004 considering the linear elastic behavior and ultimate strain value of FRPs. Still, there is room to increase the strain limit to improve the efficiency of the recommendations.
9. As average strain on stirrups is 4712 and maximum strain is 5890 at 0.5 mm crack width, if permissible strain is increased to 0.005, the average ratio V_{Exp}/V_{pred} and SD reduces to 1.45 from 1.63 and 0.23 to 0.2 respectively.

9. Publications

1. Tarak P. Vora and Dr. Bharat J. Shah, A State of the Art Use of FRP in Prestressed Concrete Structures, 2011, *International Conference on Current Trends in Technology - NUiCONE – 2011, Nirma University, Ahmedabad*, pp 1-6.

2. Tarak P. Vora and Dr. Bharat J. Shah, A Comprehensive Review on Shear Capacity of FRP Reinforcement in RC and PC Structures, 2012, *Structural Engineering Convention*, SEC-12, S.V.N.I.T., pp 431-437.

3. Tarak P. Vora and Dr. Bharat J. Shah, A Comparative Study of Deflection and Crack Patterns of RC Beams Strengthen in Flexure With GFRP Laminates, *Structural Engineering Convention*, SEC-14, IIT Delhi, pp 4323-4337.

4. Tarak P. Vora and Dr. Bharat J. Shah, Theories and Recommendations for Shear Analysis of Concrete with FRP Reinforcement, *International Journal of Advance Research in Engineering, Science & Technology*, Vol. 3(4), pp 195-202.

Papers in Communication

1. Tarak P. Vora and Dr. Bharat J. Shah, Parametric Study for Shear Capacity of Reinforced Concrete Beam Having GFRP Reinforcement, *International Journal of Civil & Structural Engineering.*

2. Tarak P. Vora and Dr. Bharat J. Shah, Experimental investigation on shear capacity of RC beams with GFRP rebar & stirrups, *Steel & Composite Structures* (SCI Indexed : Impact Factor – 0.964).

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