Experimental study on mechanical properties of FRP components and comparison of steel properties

Liang Yu [1, a*], Yan Li [2,b], Lu Chen [3,c], Chaoyi Kang [4,d] and Tianyi Zhang [5,e]
[1] Gold Mantis School of Architecture, Soochow University, Suzhou, 215123,China
[2] Department of Civil Engineering, Tongji Zhejiang College,Jiaxing,314000, China
[3] Department of Civil Engineering, Tongji Zhejiang College,Jiaxing,314000,China
[4] Department of Civil Engineering, Tongji Zhejiang College,Jiaxing,314000,China
[5] Department of Civil Engineering, Tongji Zhejiang College, Jiaxing,314000,China
[a] yuliang_163cn@163.com, bqingguose@163.com, [c] bark719@163.com ,[d]kangchaoyi@vip.qq.com, [e] 387780626@qq.com

Keywords: Fiber Reinforced Plastic (FRP); Tensile Strength; Compressive Strength; Elastic Modulus

Abstract: In order to study the applicability of the Fiber Reinforced Plastic (FRP) composite materials for light structure, a tensile compression test of a large number of FRP samples was carried out. Through statistically analysis of test data, we get the FRP's basic mechanical parameters like tensile strength, elongation, elastic modulus and we get the stress-strain curves. Compared with steel material properties, the tensile strength of the FRP is close to steel, but the elastic modulus is lower than steel's elastic modulus.

Preface

Fiber Reinforced Plastic is also named Glass Fiber Reinforced Plastic, which is made of glass fiber or its products. [1]Due to the use of different resins, there are like polyester glass fiber, epoxy glass fiber, glass fiber reinforced phenolic. FRP is light and hard, not conductive, stable performance, high mechanical strength, corrosion resistance, and it can be used instead of steel to manufacture parts and automobiles, ships, and so on.[2]

In recent years, FRP is obtained successful application of a high performance structural material in civil engineering structures, and has become an important supplement to the concrete, steel and other traditional materials.[3] But application of FRP material as a structural component is a frontier subject in the field of architecture, if FRP is used in light constructions, research and development of a new building materials and new building structure forms will greatly increase the scope of application of China and even the world in the field of building structures.[4]

In order to study the applicability of FRP in light weight structural components, we need to know the basic mechanical properties of FRP, including the corresponding strength, elastic modulus and stress-strain curves. [5]Therefore, firstly, we need to solve the problems that the mechanical properties of FRP tests. Because of the development of FRP materials, the application scope is becoming wider, FRP's working environment is not limited in normal temperature, also at high temperature. Due to the use of different temperature, its mechanical properties are also different, compared with normal temperature, its performance will greatly different. Therefore, we have high temperature mechanical properties tests. Finally, compared with the experimental data and steel material properties, we will discuss the feasibility of FRP used in structure components.

Experiments Planning

The Design of Experiments

This experiment mainly carries on tests of uniaxial tension and vertical compression tests of FRP under the normal temperature and high temperature. Through a large number of test data, we get the basic mechanical parameters, such as strength, elastic modulus and stress-strain curves. Please see Table 1 to realize specific experimental design.

Table 1 Specific Experimental Design

Temperature	Projects	Parameters	Amounts
Normal 100^0C 150^0C 200^0C 250^0C	Tensile Test	Tensile Strength	10
		Breaking Elongation	
		Tensile Elasticity Modulus	
		The Tensile Secant Elastic Modulus	
	Compression Test	Compressive Strength	5
		Compression Modulus	

Samples

The shape and size of the tensile test sample is shown in Fig.1, and the sample from the end to the working section has a radius R=75mm circular transition zone. The number of samples is not less than

The shape and size of the compressed samples are shown in Fig.2, which is a prism of a rectangular cross section. When the sample thickness is less than 10mm, slenderness ratio is 10. If there is a failure in the test process, slenderness ratio is 6. When the compression modulus is determined, slenderness ratio is 15 or according to samples deformation of the instrument. The number of samples is not less than 5.

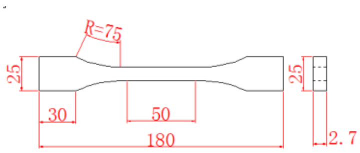

Fig.1 Tensile Test Sample Size (mm)

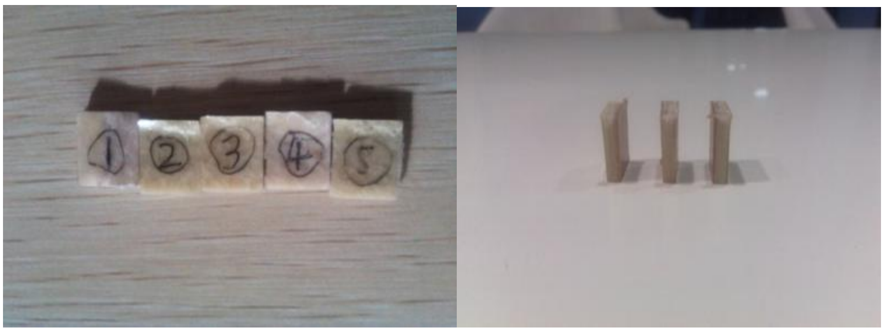

Fig.2 Compression Test Samples (Vertical Compression)

Experiment Devices and Major Experiment Procedures

Fig.3 Tension and Compression Universal Testing Machine

Fig.4 High Temperature Heating Box

(1) Numbered qualified samples, strike in samples and test the width and thickness of every sample’s working section, and calculate mean value of width and thickness.
(2) When doing high temperature tensile test, samples are loaded into the heating box (Fig.4) in normal temperature. Then, rise to required temperature with heating box, keep temperature for a while, then start experiments.
(3) Put samples into universal testing machines (Fig.3), holding samples and the center line of samples is aligned with the center line of the upper and lower clamps.
(4) Install the equipment of measuring deformation in working section, then, give samples initial force (about 5% of crippling load), check, adjust samples and the system of measuring.
(5) When test tensile modulus, tensile elongation, secant elastic modulus and stress-strain curves, loading speed is 2mm per minute, when test tensile strength, loading speed is 5mm per minute.
(6) When test tensile modulus of elasticity, we use hierarchical loading, range is 5% to 10% of crippling load.
(7) When test tensile compressive strength, we use successive loading, record crippling load and the form of crippling samples.

Calculating Parameters:
(1) Tensile Strength

$$\sigma_t = \frac{P}{bh} \tag{1}$$

σ_t - Tensile strength (MPa)
P-Crippling load (KN)
b-The width of samples (mm)
h-The height of samples (mm)

(2) Elongation when tensile failure or maximum loading

$$\varepsilon_t = \frac{\Delta l_b}{L_0} \times 100\% \tag{2}$$

Δl_b - Elongation when tensile failure or maximum loading (%)
L_o-Initial scale distance (mm)
(3) Tensile Modulus of Elasticity

$$E_t = \frac{\Delta P L_0}{bh\Delta L} \quad (3)$$

Et-Tensile modulus of elasticity (GPa)
ΔP- Loading increment of initial straight line segment on load deformation curves (kN)
ΔL-The deformation increment corresponding to the load increment (mm)
(4) Tensile Secant Elastic Modulus

$$E_x = \frac{P_x L_0}{bh\Delta L_x} \quad (4)$$

Ex- Tensile secant elastic modulus when strain is 0.1% (GPa)
Px- Load deformation curves is generated on the specified strain corresponding to the load value (kN)
ΔLx- The deformation value of the corresponding standard distance Lo from the load Px (mm)
(5) Compressive Strength

$$\sigma_c = \frac{P}{bh} \quad (5)$$

P-Crippling load (KN)
b-The width of samples (mm)
h-The height of samples (mm)
(6) Compression Modulus

$$E_c = \frac{\Delta P L_0}{bh\Delta L} \quad (6)$$

Ec- Compression modulus (GPa)
ΔP- Load increment of the initial straight line segment on the load deformation curves (kN)
ΔL- The deformation increment of the corresponding standard distance Lo from the load ΔP (mm)

Analyzing the Results of Tensile Test

FRP's Uniaxial Tensile Mechanical Properties in Normal Temperature

50 groups of samples, each time get 10 groups have tensile failure tests in normal temperature (as shown in Fig. 5), the experimental data were statistically analyzed, and the average value was calculated as follows:

Fig.5 Tensile Failure of Samples

(1) From Fig.6 we can see that FRP samples under uniaxial tensile stress, stress and strain is basically linear relation, in strain 0.0065 position, the slope slightly slow.

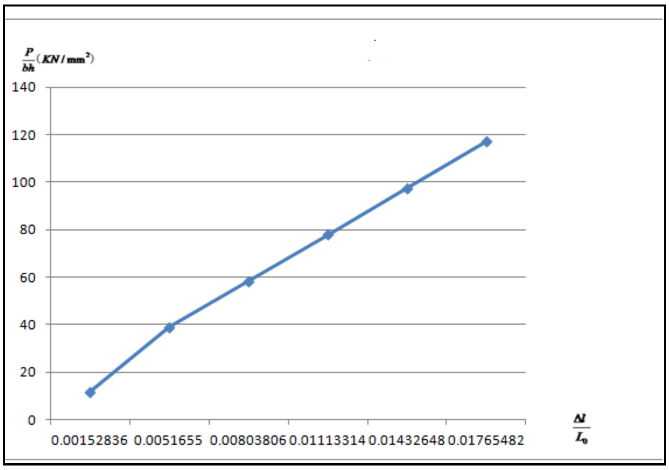

Fig.6 Tensile Test Stress-Strain Curves in Normal Temperature

(2) From the table 2 and table 3, the tensile strength of FRP samples about 293MP, breaking elongation is 5.776%, elastic modulus is 6246MP.

Table 2 Tensile Test in Normal Temperature and Results 1

Crippling Load (kN)	Elongation (mm)	Tensile Strength $\sigma_t = \frac{P}{bh}$ (MPa)	Breaking Elongation $\varepsilon_t = \frac{\Delta l_b}{L_0} \times 100\%$
7.432	2.888	293.75	5.776%

Table 3 Tensile Test in Normal Temperature and Results 2

Tensile Modulus of Elasticity $E_t = \frac{\Delta P L_0}{bh\Delta L}$ (MPa)	Tensile Secant Elastic Modulus $E_x = \frac{P_x L_0}{bh\Delta L_x}$ (MPa)
6246	7009.894

(3) In a certain range of FRP's thickness, there is a linear relationship between the thickness of FRP and its crippling load and elongation, as shown in Fig.7 and Fig.8. From Fig.7 and Fig.8 can be seen that, with the increase of the thickness, the amount of breaking elongation and crippling load have decreased. So the thickness of FRP is one of factors affect the accuracy of the experiment.

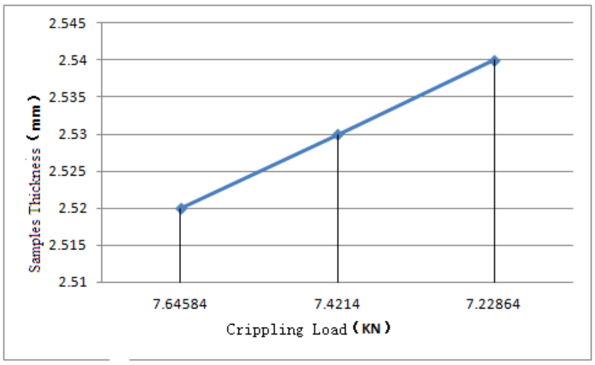

Fig.7 Samples Thickness and Crippling Load

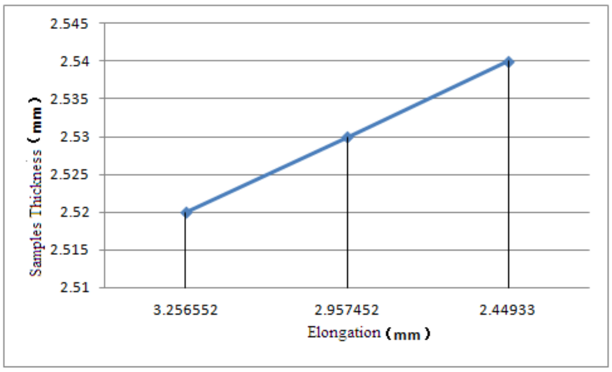

Fig.8 Samples Thickness and Elongation

Effect of High Temperature on Tensile Mechanical Properties of FRP

(1)From Fig.9, we can be seen that the stress-strain curves of FRP have little effect on high temperature or normal temperature, and the gradient of FRP stress and strain curves has a little change with temperature increasing.

(2)From Fig.10 and Fig.11, we can see that the tensile strength of FRP increases from normal temperature to 200 degree, decreases from 200 to 250 degree, also we can see that maximum loading elongation or breaking elongation of FRP increases from normal temperature to 200 degree, decreases from 200 to 250 degree.

(3)From Fig.12 we can see that the effect of temperature on the tensile modulus of FRP is very small.

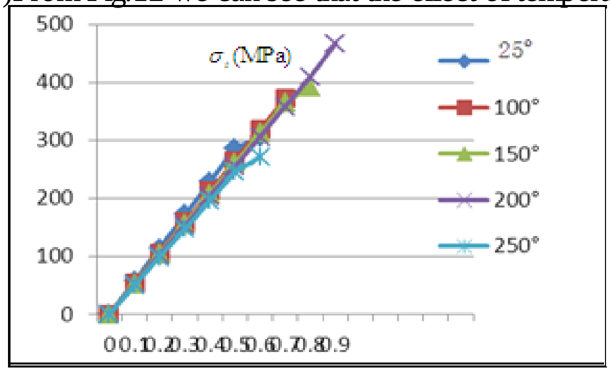

Fig.9 Stress Strain Curve in Different Temperature

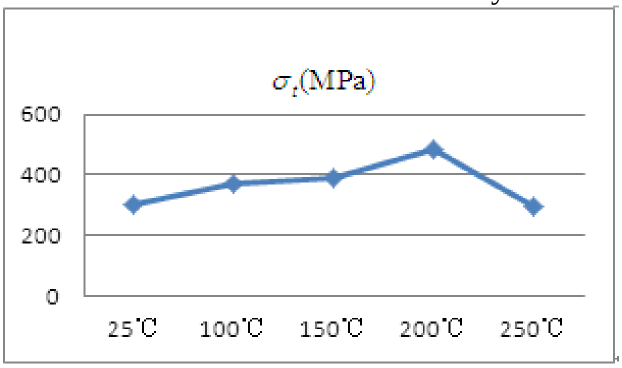

Fig.10 Changes of Breaking Stress in Different Temperature

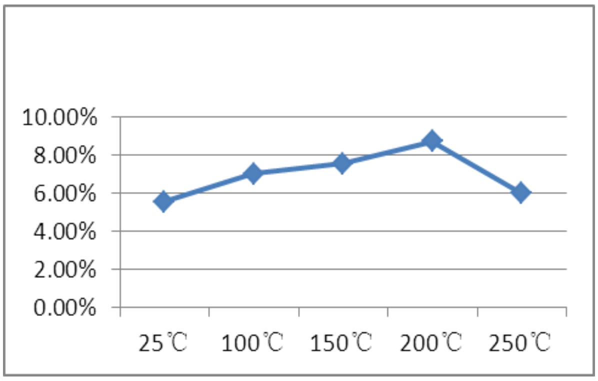

Fig.11 Changes of Elongation in Different Temperature

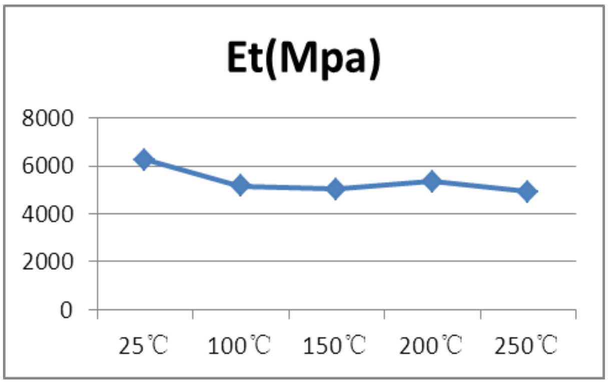

Fig.12 Changes of Tensile Modulus of Elasticity in Different Temperature

Analyzing the Results of Compression Test

FRP's Basic Compression Mechanical Properties in Normal Temperature

Take 5 groups of FRP samples totally in compression test, test data as shown in Table 4-1 and Table 4-2. Data from Table 4-1 and Table 4-2 substituted into Equation 5 and Equation 6 and calculate samples of compression strength and compression modulus, as shown in Table 5.

Table 4-1 Data of Compression Test 1

Loading Speed 2mm/min	Average Thickness（mm）	Average Width（mm）	Average Height（mm）	Crippling Load（kN）	Displacement（mm）
Sample 1	2.50	10	12	7.686	0.274
Sample 2	2.65	10	12	3.976	0.171
Sample 3	2.62	10	12	5.262	0.208
Sample 4	2.52	10	12	6.420	0.266
Sample 5	2.66	10	12	4.483	0.288

Table 4-2 Data of Compression Test 2

Loading Speed 2mm/min	Initial Load 150N	First Load 400N	Second Road 800N	Third Load 1200N	Fourth Load 1600N	Fifth Load 2000N
	Load corresponding variable at all levels（mm）					
Sample 1	0.021	0.032	0.048	0.065	0.079	0.093
Sample 2	0.021	0.033	0.051	0.066	0.083	0.098
Sample 3	0.021	0.032	0.047	0.063	0.078	0.092
Sample 4	0.022	0.036	0.054	0.071	0.088	0.104
Sample 5	0.035	0.065	0.118	0.141	0.162	0.181

Table 5 The Results of Compression Test

Compression Test	Compressive Strength $\sigma_c = \frac{P}{bh}$ （MPa）	Compression Modulus $E_c = \frac{\Delta P L_0}{bh\Delta L}$ （GPa）
Sample 1	307.44	12.8
Sample 2	150.03	11.56162
Sample 3	200.84	12.21374
Sample 4	254.76	11.42857
Sample 5	168.53	11.592911

From Table 5, we can see that only sample 2 different from others, so we take data from sample 1.3.4.5 as the source data, and calculate average value, see Table 6. From Table 6 we can see that compression module of FRP is very low.

Table 6 Parameters of Compression Test

Compression Test	Compressive Strength $\sigma_c = \frac{P}{bh}$ （MPa）	Compression Modulus $E_c = \frac{\Delta P L_0}{bh\Delta L}$ （GPa）
Loading Speed 2mm/min	254.347	12.14744

Effect of High Temperature on the Mechanical Properties of FRP

From Fig.13, we can see that, less than 100 degree, with temperature increasing, compressive strength slightly increased. When temperature more than 100 degree, FRP's compressive strength has greatly influenced by temperature. With temperature increasing, compressive strength of FRP decreases significantly.

From Fig.14 we can see that the increase of temperature has a great influence on the modulus of elasticity. Compression modulus decreases with temperature increasing.

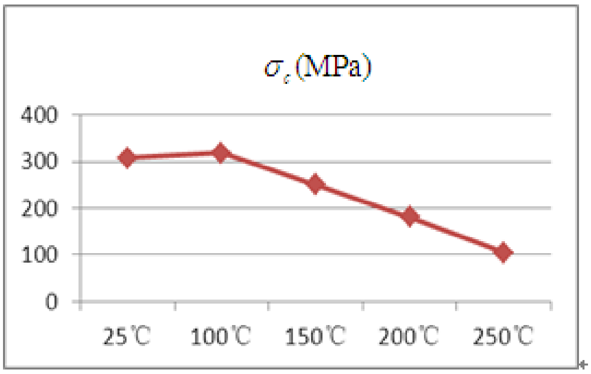

Fig.13 Changes of Compressive Strength in Different Temperature

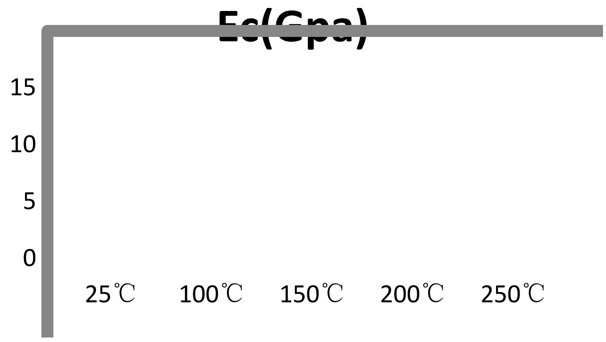

Fig.14 Changes of Compression Modulus in Different Temperature

Compared with Q235 Steel and FRP

Compared with Strength and Modulus of Elasticity

Table 7 Compared with Q235 Steel and FRP

	Breaking Stress (MPa)	Failure Strain	Modulus of Elasticity (MPa)
Q235 Steel	235/0.85	≈0.1%	2.0×10^5
FRP	Tensile Strength: 293.75 Compressive Strength: 254	5.7756%	6246
Comparison	FRP≈Q235 Steel	FRP>Q235Steel	FRP<Q235 Steel

From Table 7 we can see that, tensile stress and compressive stress of FRP are close to Q235 steel, but strain is higher than Q235 steel. Therefore, in terms of tensile strength, the same size of FRP stronger than Q235 steel, but at the same time, FRP with a greater deformation. But the quality of FRP is lighter, and the cost of FRP is cheaper, so in some specific components, or maybe it is only required to consider that tensile strength of FRP can replace Q235 steel.

Comparison of temperature variation on material properties

Tensile strength of FRP increases with temperature increasing from normal temperature to 200 degree, but decrease from 200 to 250 degree, also, maximum load elongation and breaking elongation of FRP increases with the increase of temperature from normal temperature to 200 degree, but decrease from 200 to 250 degree. Bending strength and compressive strength are decreased with the increase of temperature from normal temperature to 250 degree. When steel is higher than 200 degree, with the increase of temperature, tensile strength, yield point and elastic modulus of steel are all changed, the overall trend is strength decrease, plasticity increase. When temperature is about 250 degree, tensile strength of steel has increase slightly, but plasticity of steel has decrease.

Conclusions

Through experiments, we can draw a conclusion that tensile properties of FRP and Q235 steel are very similar, and FRP has the advantages of light weight, low cost and other advantages. FRP is a feasible structure component of traditional light steel.

References

[1]BaneIjee J.R, Exact Bemoulli,Euler static flti~I1CS8 mattrix for a range of tapered beam-eolumm [J] International Journal Num Mathematical Engineering, 1986, 23(9):1615-1628

[2] Cleghom W.L, Tabarrok B.Finite element formulation of a tll~roed Timoshenko beam for free vibration analysis [J] J. Of Sound&rib, 1992, 152 (3):461470

[3] Ye Lieping,Fen Peng,Applications and development of fiber-reinforced polymer in engineering stuctures,CHINA CIVIL ENGINEERINGJOURNAL, 2006,39(3):24-36, In Chinese

[4] Yao Jian,Teng Jingguang, Experiment study on bond strength between FRP and concrete[J]Journal of Building Structures,2003,24（5）：10-23，In Chinese

[5] Feng peng,Jin Fei-fei,Ye Lie-ping,Research on Stuctural Performance and Design Indices of FRP Footbridges[J] Journal of Architecture and Civil Engineering,2022,28(3):14-22, In Chinese