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The tensile properties of GFRP bars at different loading rates

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ABSTRACT
In order to study the effect of loading rates on the tensile property indexes of GFRP (Glass Fiber Reinforced Polymer) bars, the tensile property experiments were conducted at four different loading rates by utilizing the electro-hydraulic servo universal testing machine. The results show that: with increases in loading rate, the ultimate tensile strength and the ultimate tensile strain increase, while the elastic modulus almost remains constant with the average value 28.5 GPa; the failure mode of specimens belongs to splitting failure and the stress-strain curves show a linear relationship. Based on the results and analyses, a loading rate of 2 mm/min is recommended when conducting experiments to determine the tensile property indexes of GFRP bars.
KEYWORDS: GFRP bar; tensile property; loading rate; stress-strain curve; elastic modulus

1. INTRODUCTION

GFRP bar (Glass Fiber Reinforced Polymer bar) is a composite made up of a resin matrix and continuously twistless glass fiber reinforcement though the pultrusion process. Compared to rebar, it boasts advantages such as being light-weight, high strength, chemical corrosion resistant (Micelli et al., 2004; Kim et al., 2008), fatigue resistant (Uomoto and Nishimura, 1995), anti-electromagnetic and inflaming retardant, thus becoming an ideal alternative which is gradually applied in civil (and mining) engineering fields (Liu and Zhou, 2014.). Rebar is a plastic material while GFRP bar is a brittle material; therefore the structure design concepts of the two are different. In order to ensure the safety of the structure design, it is essential to deeply study the mechanical properties of GFRP bar. However, in terms of tensile loading rate, there are some differences among experiment specifications and researchers when conducting the tensile experiment to determine the tensile property indexes of GFRP bar.

"ACI 440.1R-03" (ACI Committee 440, 2003a) provides that the tensile loading rate should be controlled at 100-500 MPa/min and "ACI 440.3R-04" (ACI Committee 440, 2004b) provides that the specimen should be damaged in 1-10 min, no matter what load control or displacement control is adopted. "GB/T1447-2005" (GAQSIQ of the PRC and Standardization Management Committee of the PRC, 2005a) and "GB/T 13096-2008" (GAQSIQ of the PRC and Standardization Management Committee of the PRC, 2008b) also provide that the tensile loading rate should be controlled at 5 mm/min when determining the ultimate tensile strength and 2mm/min when determining the elastic modulus as well as the ultimate tensile strain. Moreover, there are several specifications that not give a specific loading rate when conducting the tensile experiment, such as "MT/T 1061-2008" (State Administration of Work Safety, 2008) and "JG/T 351-2012" (MHURC of the PRC, 2008).

It is the fact that the loading rates adopted by the researchers are also not the same when they carried out in tensile experiments. For example, Brahim Benmokrane (Benmokrane et al., 2000) adopted a loading rate of 250 MPa/min when he researched the tensile properties of AFRP and CFRP bars. Young Jun You (You et al., 2007) adopted the loading rate according to the specification "ASTM-D-3916" (ASTM, 2002) when he conducted the tensile experiments of FRP bars. There was no specific loading rate given by S. Kocaoz (Kocaoza et al., 2005) when he studied the tensile properties of GFRP bars. Besides the researchers mentioned above, there have also been a wide range of researchers from China completing tensile experiments of GFRP bars, and the loading rates they chose also varied widely. $5\times10^{-5}s^{-1}$ were used by Jikai Zhou (Zhou et al., 2008) 4kN/time by Jing Chen (Chen et al., 2012), 2 mm/min by Xinyue Zhang (Zhang et al., 2005). Particularly, Guowei Li (Li et al., 2012) adopted a group of loading rates which were 2, 4, 6, 10, 15 mm/min to research their effect on the tensile property indexes of GFRP bars.

In this paper, in order to study the effect of

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loading rates on the tensile property indexes of GFRP bars, four different loading rates were adopted, which were 2, 10, 20, 50 mm/min respectively.

2. EXPERIMENTAL PROGRAM

2.1 Experimental materials

The whole thread GFRP bars adopted in this paper are produced by Shandong Safety Industrial Co., Ltd., which have right-handed thread. The pitch of this GFRP bar is 10 mm, and the inner diameters as well as the outer diameter are 18 mm and 20 mm, respectively. The matrix material is unsaturated resin and the reinforcement is the ECR24-2400D-601 type glass fiber produced by Shandong Glass Fiber Composite Co., Ltd. The specifications of seamless steel pipe are: 38 mm in outer diameter, 6.5 mm in thickness, and 50 mm in length; the efficient silent broken agent is produced by Beijing Yuyi special cement plant and the recommended water cement ratio is 28%-35%; the type of strain gauge is BX120-5AA and the value of sensitivity coefficient K is 2.08.

2.2 Specimens preparation

Due to the low transverse strength of GFRP bar, if the clamping is directly carried out at the ends, it will be quickly crushed before the tensile failure occurs. In order to avoid this defect, both ends of GFRP bar are protected by the seamless steel pipes, and are bonded by the efficient silent broken agent, thus relying on the huge expansion pressure to provide axial shear stress.

ACI 440.1R-03 (ACI Committee 440, 2003a) and ACI 440.3R-04 (ACI Committee 440, 2004b) recommend that the effective tensile length should be no less than 40 times as long as the nominal diameter of the GFRP bar and should be no less than 100 mm. JG/T 351-2012 (MHURC of the PRC, 2008) also provides that the effective tensile length should be 400-600 mm. Due to the limitation of the maximum tensile space of WAW-600B type electro hydraulic servo universal testing machine used in this experiment, the specifications of specimens are made as follows: the full length is 600 mm, and the anchorage length at both ends is 200 mm, thus the rest effective tensile length is 200 mm. The schematic sketch of the specimen is shown in Figure 1.

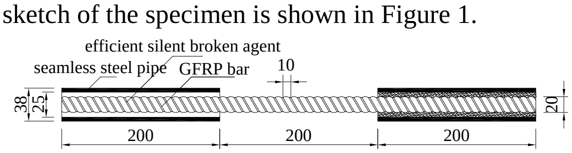


Figure 1: The schematic sketch of the specimen.

2.3 Experimental instruments

The instruments used in this experiment include WAW-600B type electro hydraulic servo universal testing machine and XL2118C type stress-strain comprehensive parameter testing instrument, as shown in Figure 2.

Figure 2: WAW-600B type electro hydraulic servo universal testing machine and XL2118C type stress-strain comprehensive parameter testing instrument.

2.4 Experimental methods

The tensile experiments are conducted by utilizing WAW-600B type electro hydraulic servo universal testing machine with the displacement control method adopted and the loading rate were 2, 10, 20, 50 mm/min respectively. The tensile strain were recorded by XL2118C type stress-strain comprehensive parameter testing instrument with the quarter-bridge connection method used, and the strain gauge was attached to the middle area of the specimen.

3. EXPERIMENTAL RESULTS AND ANALYSES

The experimental results of tensile properties of GFRP bars at different loading rates are listed in Table 1.

3.1 The load-displacement curves and the stress-strain curves

The load-displacement curves and the stress-strain curves are shown in Figures 3 and 4, respectively. During the experiment, the strain gauges were destroyed due to the deformation of the specimen. As a result, the strain value in the second half of the tensile experiment process was not recorded.

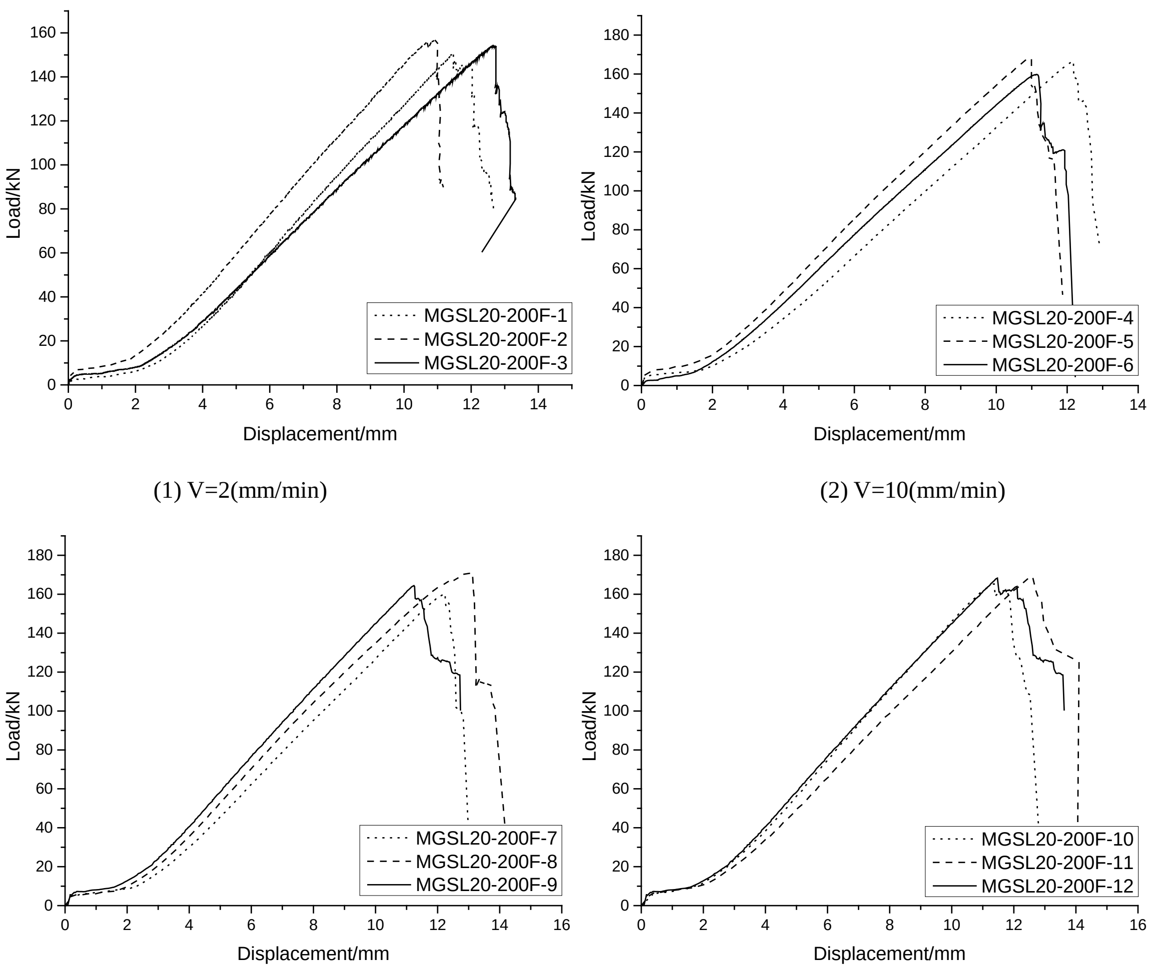
As shown in Figure 3, there are platforms about 2 mm in the initial stage because there are minimal gaps between the clamps and the slots. If pre-loading is applied, then these platforms can be eliminated. It can be seen from Figure 4 that the stress-strain curves are consistent with the load-displacement curves in terms of the trends, which display a linear relationship.

3.2 Failure mechanism

During the experiments, there is no occurrence of anchorage failure, which indicates that this anchorage method is effective and reliable. The tensile failure mode belongs to splitting failure. To be precise, the fiber split is evenly distributed throughout the entire scale of effective tensile length and it looks like a lantern as the fibers are scattered after splitting. The splitting failure mode is shown in Figure 5.

Table 1: The experimental results of tensile properties of GFRP bars at different loading rates.

Specimen No.	Loading rate V(mm/min)	Ultimate load F_u(kN)		Ultimate strength σ_u(MPa)		Elastic modulus E(GPa)		Ultimate tensile strain ε_u(%)	
MGSL20-200F-1		150.88		480.5		31.0		1.55	
MGSL20-200F-2	2	157.06	154.18	500.2	491.0	27.6	29.5	1.81	1.67
MGSL20-200F-3		154.60		492.4		30.0		1.64	
MGSL20-200F-4		166.80		531.2		26.2		2.03	
MGSL20-200F-5	10	168.04	164.88	525.2	525.1	26.0	27.4	2.06	1.93
MGSL20-200F-6		159.80		509.0		29.9		1.70	
MGSL20-200F-7		160.54		511.3		25.7		1.99	
MGSL20-200F-8	20	170.92	165.30	544.3	526.4	27.8	27.8	1.96	1.90
MGSL20-200F-9		164.45		523.7		30.1		1.74	
MGSL20-200F-10		165.28		526.4		31.9		1.65	
MGSL20-200F-11	50	169.08	167.54	538.5	533.6	27.3	29.3	1.97	1.83
MGSL20-200F-12		168.26		535.9		28.8		1.86	



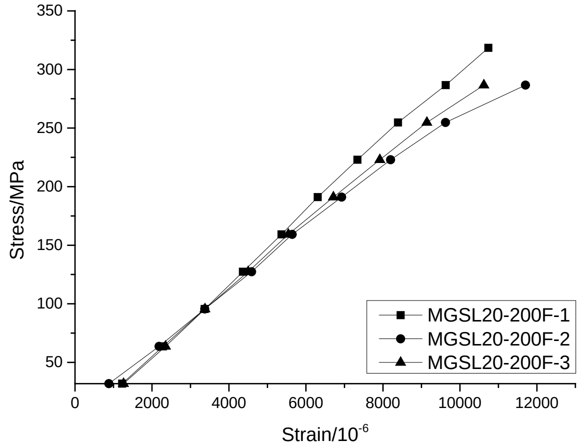
(1) V=2(mm/min)

(2) V=10(mm/min)

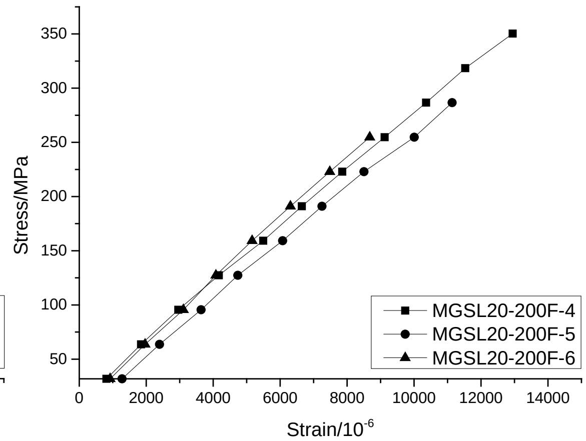
(3) V=20(mm/min)

(4) V=50(mm/min)

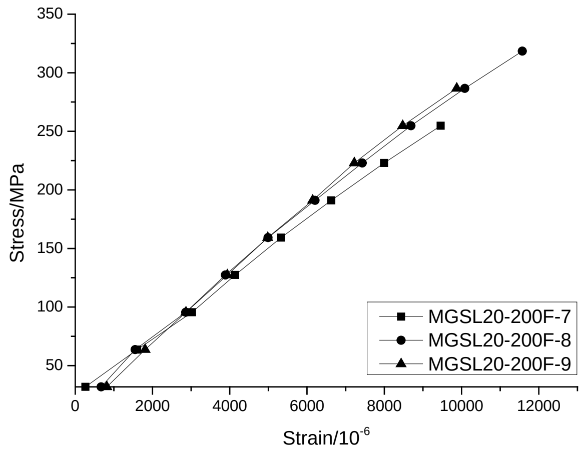
Figure 3: The load-displacement curves.



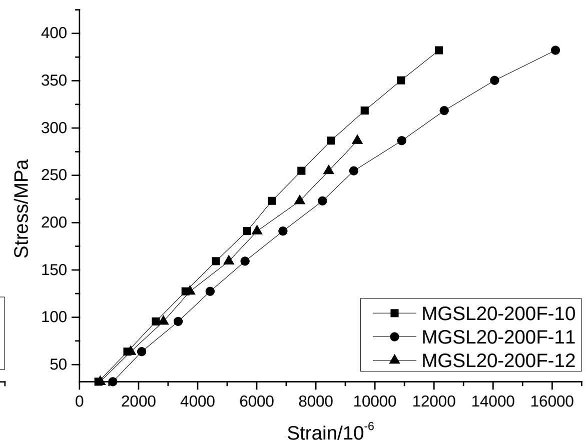
(1) V=2(mm/min)



(2) V=10(mm/min)



(3) V=20(mm/min)



(4) V=50(mm/min)

Figure 4: The stress-strain curves.

Figure 5: The splitting failure mode.

In the process of experiments, when the load is increased to about 45% of the ultimate load, the resin and the fibers begin to split, accompanied by a clear and crisp sound. With the increase of the load, the splitting sound is continuous, and white cracks can be clearly seen on the splitting spot at the same time. When it nearer to the failure load, the splitting sound becomes louder and more concentrated, and the fibers are split from the outside layer to the inside layer. Finally, the specimen is damaged, accompanied with an abruptly loud sound.

Based on the analyses of experimental phenomena mentioned above, the tensile failure mechanism of GFRP bars can be interpreted as follows: in the loading process, the external fibers firstly bear the stress, and then the resin matrix transfers them to the internal fibers. Therefore, it is not uniformly and equivalently distributed on the cross section, but an inversely trapezoidal distribution that the stress gradually decreases from the circumference to the center. That is to say, with the increase of the stress, the external fibers firstly reach the ultimate stress and fracture with the stress redistribution at the same time. As the stress continues to increase, the fibers fracture gradually from the external layer to the internal layer, and eventually the specimen is damaged. The failure mode belongs to brittle failure.

3.3 Ultimate strength

The ultimate strength of GFRP bars at different loading rates is shown in Table 1 and Figure 6.

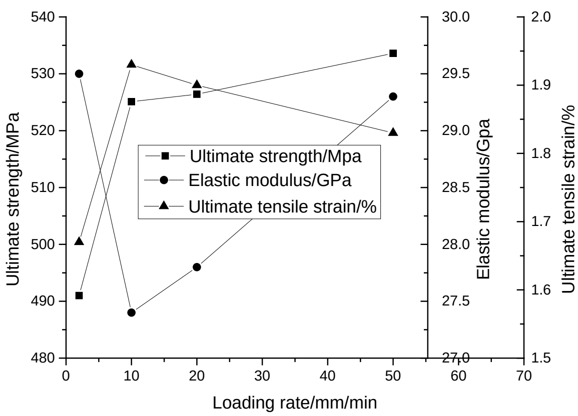


Figure 6: The trend graph of property indexes of GFRP bars.

As can be seen from Table 1, the ultimate strengths are 491, 525.1, 526.4, and 533.6 MPa when the loading rates are 2, 10, 20, 50 mm/min, respectively. Compared to loading rate of 2 mm, the ultimate strength at loading rates of 10, 20, and 50 mm/min increases by 6.9%, 7.2%, and 8.7%, respectively. When comparing the latter loading rate with the former one, the corresponding ultimate strength is increased by 6.9%, 0.3%, and 1.4%, respectively.

According to Figure 6, it is particularly noticeable that the ultimate strength sees a dramatically increasing trend between the loading rates of 2mm/min and 10 mm/min, and afterwards it grows upwards steadily. This is because the stress on the cross section of GFRP bar is an inversely trapezoidal distribution, which leads to the fact that the external fibers reach the ultimate stress and fracture before the internal fibers. When the loading rate is lower, there is enough time for the external fibers to reach the ultimate stress and fracture, which precedes the external fibers. Consequently, they are not fractured in the meanwhile so that the ultimate strength is lower. However, when the loading rate is higher, there is not enough time for the external fibers to precede the internal fibers, and they almost reach the ultimate stress and fracture at the same time, thus the ultimate strength is higher.

It is clear that the ultimate strength increases significantly when the loading rate of 2 mm/min changes into 10 mm/min and the increase is relatively higher when the loading rate exceed 10 mm/min. Taking the above factors into consideration of engineering safety, a loading rate of 2 mm/min is recommended when conducting experiments to determine the tensile ultimate strength of GFRP bars.

3.4 Elastic modulus

Due to the instability of the strain values recorded by the instrument in the latter loading stage, the strain values in the former loading stage, which are relatively stable, are used to calculate the elastic modulus. The calculation formula is shown as follows:

$$E = \frac{F_1 - F_2}{(\varepsilon_1 - \varepsilon_2)A}$$

Where E is the elastic modulus of specimen, and the unit is GPa; A is the cross-sectional area of specimen, and the unit is mm^2; F_1, ε_1 are the load which is $20\,kN$ and its corresponding strain, and the units are kN and dimensionless; F_2, ε_2 are the load which is $50\,kN$ and its corresponding strain, and the units are kN and dimensionless.

As can be seen from Table 1 and Figure 6, all of the elastic moduli of the specimens range between 25.7 GPa and 31.9 GPa, and the average value is 28.5 GPa. When the loading rates are 2, 10, 20, and 50 mm/min, the average values of the elastic moduli are 29.5, 27.4, 27.8, and 29.3 GPa, respectively, and change by 3.5%, -3.9%, -2.5%, and 2.8%, respectively compared to the average value of 28.5 GPa. As the changes are small and there is no obvious regularity, it is believed that the loading rates have little effect on the elastic modulus.

3.5 Ultimate tensile strain

The calculation formula of the ultimate tensile strain is as follows:

$$\varepsilon_u = \frac{F_u}{EA}$$

Where ε_u is the ultimate tensile strain, and the unit is dimensionless. F_u is the ultimate load, and the unit is kN.

As can be seen from Table 1, when the loading rates are 2, 10, 20, and 50 mm/min, the average values of the ultimate tensile strain are 1.67%, 1.93%, 1.90%, and 1.83%, respectively. Compared to a loading rate of 2 mm, the ultimate tensile strain at loading rates of 10, 20, and 50 mm/min increases by 15.7%, 13.7%, and 9.6%, respectively. Comparing the latter loading rate with the former one, the corresponding ultimate tensile strain increases by 15.7%, -1.7%, and -3.6%, respectively.

Theoretically, as the elastic modulus is an intrinsic property of GFRP bar, the trend of the ultimate tensile strain should resemble the trend of the ultimate strength with the increases in loading rate in Figure 6. In reality, this is not the case and they see an opposite trend after the loading rate of 10 mm/min. This non-conformity can be interpreted by the discreteness of the elastic moduli, which are obtained through calculation.

4. CONCLUSIONS

Based on the above experimental results and analyses, it can be concluded that:

With loading rate increases, the ultimate tensile strength and the ultimate tensile strain increase, while the elastic modulus remains almost constant with the average value at 28.5 GPa;

The failure mode of specimens belongs to splitting failure, and the fibers gradually fracture from the external layer to the internal layer.

The stress-strain curves show a linear relationship, which belongs to the scope of elastic deformation.

A loading rate of 2 mm/min or less is recommended when conducting experiments to determine the tensile property indexes of GFRP bars.

The anchorage method adopted in this paper is effective and reliable, but utilizing the strain gauges to record the strain values should be improved, and an extensometer is recommended.

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