EXPERIMENTAL INVESTIGATION OF FRP RELAXATION AND ITS EFFECT ON PRE-STRESSING TECHNIQUES

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1 INTRODUCTION

Strengthening is often a necessary measure used to overcome an unsatisfactory deficient situation or where a new code requires the structure, or a member of it, to be modified to achieve new requirements.

Since the emergence of Fiber Reinforced Polymer (FRP) as a potential repair material during the last two decades, on-going research has been conducted on retrofitting of various structural components and confining compressive members using FRP. FRPs can be used for both flexural strengthening of members as well as for confinement of compression members. In each case, the materials can be used as passive reinforcement or active reinforcement; the latter requires pre-tensioning of the FRP prior to application of external loads. Because the relaxation takes place when pre-tensioning is used, the applications where pre-stressing is used in beams or columns are discussed in more details below.

Rectangular strips of FRP may be used for strengthening of reinforced concrete beams and slabs. The strips can be pre-stressed and connected to the member through deviators and end-anchorages [1]. Among the advantages of this technique are a reduction of service load stresses in steel reinforcement, decreased crack width and mean crack distance, and increased resistance corresponding to the first yielding of the longitudinal steel [1].

With respect to concrete columns, retrofit of these elements often requires providing additional confining pressure. Confinement, defined as restraint to lateral dilation, has been traditionally provided for compression members through steel transverse reinforcement in the form of spirals, circular hoops or rectangular ties. Steel and concrete jackets are other techniques for providing additional confinement for compression members. When FRP is used as the confining material, a problem arises in that the strength of the FRP material is usually not utilized until the lateral strain in the confined concrete is very high. In some cases, the failure of concrete will occur before the FRP material is fully utilized. Overcoming this problem can be achieved by using active confinement, which necessitates the pre-stressing of the FRP jacket.

One of the most salient problems of pre-stressing FRPs is stress relaxation, which pertains to the decrease in the stresses with time under constant deformation. When steel is pre-stressed for active confinement of a column, only short-term mechanical properties are needed. However, when FRP is used as the confining material, the long-term tensile properties must be considered.

Creep and relaxation of FRP materials and fibers have been studied with single fibers and fiber bundles, and a considerable body of knowledge exists about the performance of these materials [2-5]. The objective of this research, however, is to investigate the relaxation of FRP materials, which nowadays are used to retrofit and strengthen RC members. In particular, the behavior of these materials when they are used to increase the confinement pressure by using active confinement techniques is of interest.

1.1 Relaxation of FRP Materials

Relaxation losses in FRP materials are caused by three sources: a) resin matrix, b) straightening of fibers and c) relaxation of fibers [6]. During initial stressing, the matrix will carry a portion of the load. However, over time, this load will be carried completely by the fibers. This type of relaxation, which depends on the modular ratio of the matrix and fiber and the fiber volume ratio, occurs in the first 24 to 96 hours of pre-stressing [6]. The second loss is dependent on the quality control during manufacturing of pultruded sections. This applies to both FRP laminates that are constructed in manufacturing plants and the accuracy of FRP saturating in wet-lay up systems that are carried out on the construction site. The fibers in the matrix are not perfectly aligned so the stress in the fibers will cause them to straighten, resulting in a second loss [6]. Finally, similar to most materials, relaxation occurs in the fibers and is dependant on the fiber type.

For most composites, the viscoelastic behavior is primarily due to the matrix. Composite materials are reinforced with fibers in part to resist creep and relaxation. The magnitude of stress relaxation in a composite structure is influenced by a variety of factors, such as material architecture, loading frequency, and climatic influences such as temperature, humidity and alkaline condition. Reinforcements, such as carbon fibers, exhibit a negligible viscoelastic behavior and, even when combined with a viscoelastic matrix, present very small amount of creep or stress relaxation in the reinforcement direction [9]. But both glass FRP and Aramid FRP show significant decrease in tensile strength when they are subjected to long-term constant load [10].

2 EXPERIMENTAL PROGRAM

In this study some different test setups were designed to simulate the FRP pre-stressing techniques. The loads were measured using load cells and strains were monitored through strain gages and extensometers during the tests. For gluing strain gages on FRP M-Bond-AE-10/15 and M-Bond GA-2 adhesives were used because they have good properties for such relaxation and creep tests. This issue was confirmed by tension testing of a steel strip during one week. The relaxation of steel in this test was approximately zero. The amounts of strains measured by strain gages which were glued with these adhesives were nearly constant against the others which glued for example with M-Bond 610. Each test lasted about 1000 hours and all experiments were carried out in a controlled room with a constant temperature of 23±1 °C and a humidity of 50%. Table 1 presents the mechanical properties of FRP fabrics, which were used in this research as provided by the manufacturer. The epoxy resin that was used consisted of two components: the main epoxy resin (Bisphenol) and the curing agent hardener (Polyamine) with a curing time of 48 hours at room temperature. The epoxy was prepared by mixing the main epoxy resin and hardener with a weight ratio of 5:2 until a homogeneous translucent blue colour was obtained.

Table 1 Mechanical properties of fabrics.

Fiber type	Tensile strength (MPa)	Ultimate strain (%)	Modulus of elasticity (GPa)	Thickness (mm)
Carbon	3800	1.55	240	0.176
Glass	3000	4.3	65	0.299
Aramid	2900	2.5	120	0.44

The first setup (Sq-sim), used to simulate the pre-stressing techniques to provide active confinement, has been proposed by *Yamakawa et al. (2001)* by pre-stressing aramid fiber belts for emergency retrofit of damaged RC columns [12]. A similar technique was conducted by *Nasrollahzadeh et al. (2004)* by pre-stressing carbon fiber belts for retrofit of short square RC columns with 250mm width and 30mm corner radii. Figure 1 shows the details of the pre-stressing method of CFRP and AFRP strips [12]. Carbon and Aramid fiber strips were cut into desired lengths and were impregnated with epoxy resin along 100~150mm lap joint of both cut ends to form a loop, which is straightened to form a two-ply strip. The two ends of the two-ply strip can be clamped together by putting a couple of crossbars into the end hooks and screwing the nuts in the end of high strength bolts which passed through the holes of crossbars. One of the benefits of this technique is that there are not any anchorage systems to pre-stressing the strips. So the only slip which may occur is pertaining to the overlap portion of strips not to strips and anchorage. Figure 2 illustrates the schematic detail of first test setup which used to simulate the relaxation of FRP strips in pre-stressing technique shown in Figure 1. The dimension of this device is equal to a 250mm square section with 30-mm corner radii, which is the same as the specimens used by *Nasrollahzadeh et al* and *Yamakawa et al.* A glair of primer was brushed on the surface of the specimen around the four corners and fine sand was sprinkled on it while it was wet to simulate a surface like concrete with approximately the same friction coefficient.

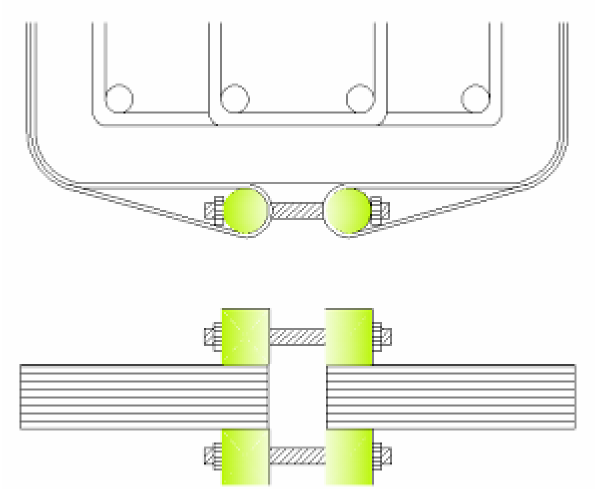

Fig. 1 Details of pre-stressing method

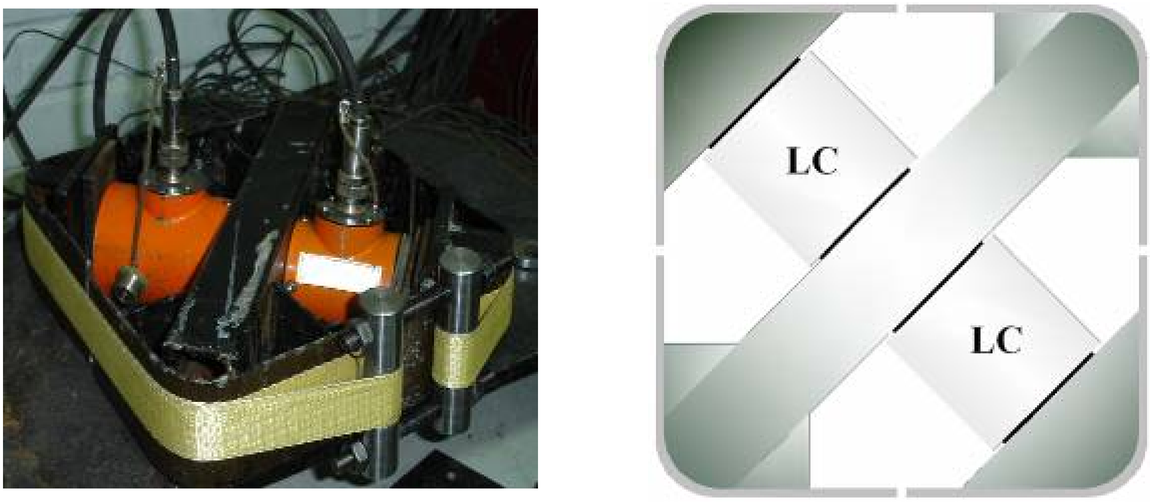

Fig. 2 Details of Sq-sim test setup

The amount of confining pressure was measured during the tests by 2 load cells in diagonal direction. The strains were measured with both strain gages and extensometers in the corner and between the adjacent corners of FRP belts that were wrapped around the test setup. In this system of pre-stressing it is not possible to wrap precured FRP strips around specimens**.** So the strips which are used in this regards are just fabrics (without resin) or wet fabrics (Before curing the resin). Also in these conditions it isn't possible to install strain gages on fabrics because there aren't any smooth places on the fabrics to install the strain gages. So, small parts of strips which the strain should be measured there were saturated with resin previously to have smooth surfaces for gluing strain gages there.

The second setup (C-sim) was used to simulate the pre-stressing techniques to provide active confinement of previous technique in circular columns Fig 3. In this system two semi-cylinders with one load cell between them were used to measure the relaxation of FRP strips in 1000 hour. The diameters of semi cylinders are 170mm. Figure 4 shows the third setup (ExGrout-sim) which was used to simulate the pre-stressing technique, which was used by many researchers by injecting pressurized epoxy resin (*Saadatmanesh et al 1996*) or using expansive grout (*Mortazavi et al 2003*) [14][15]. In this test, a pre-formed confining jacket was placed around the setup, which is illustrated in Fig. 4, and then a mix comprising cement, sand and expansive agent is inserted between the concrete cylinder and the FRP jackets. The jacket confines the expansion of the grout during the hardening period (3–4 days) and thus the chemical pre-tensioning occurs in the jacket, reacting against the setup. During the expansion of the grout, the FRP jacket and test setup were embedded in a cast to avoid any leaking from the top and bottom of the cylinders [14].

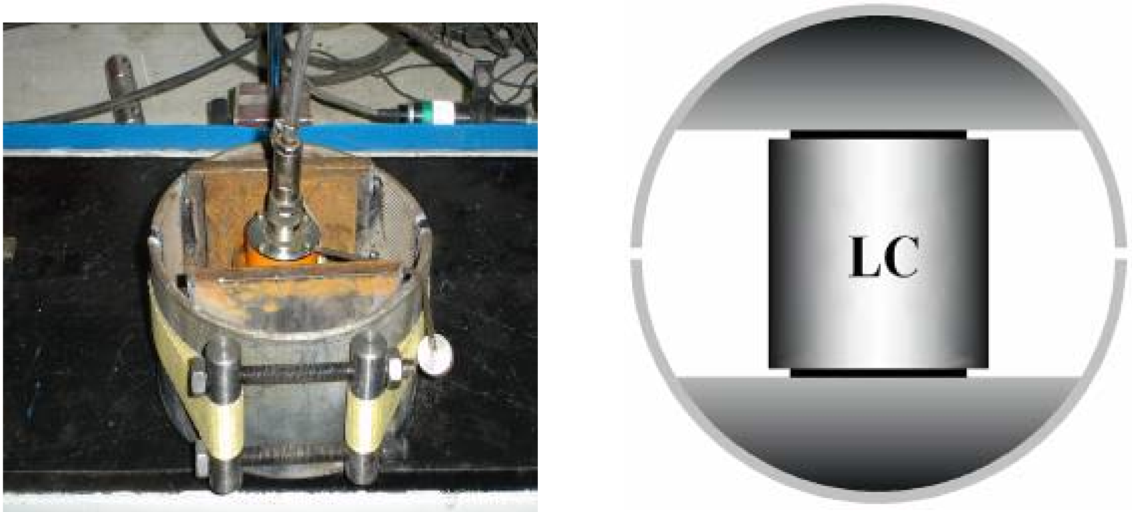

Fig. 3 Details of C-sim test setup

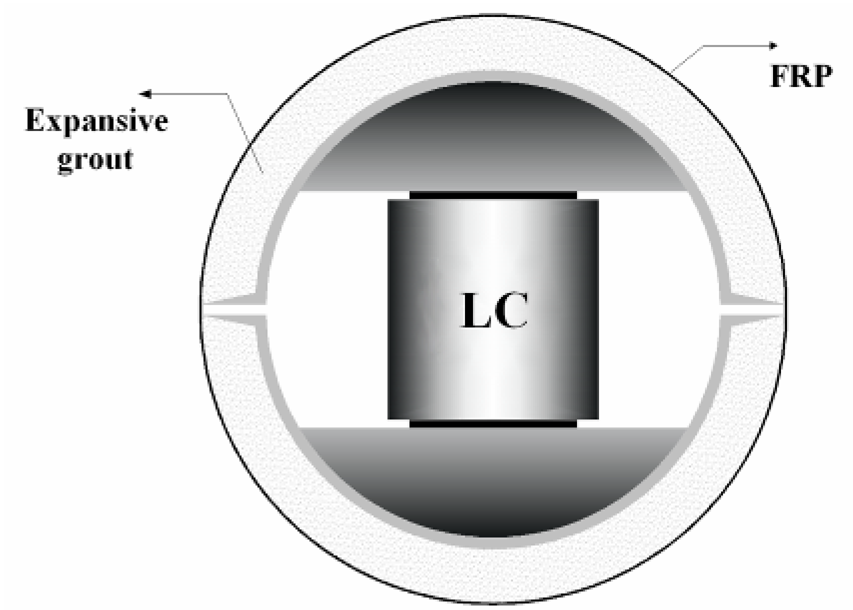

Fig. 4 Details of ExGrout-sim test setup

3 TEST RESULTS

Figure 5 shows the relaxation plots of tests. The scales of time axes are logarithmic. The vertical axes indicate the amount of loads that were measured by load cells. Because the amounts of stresses in the perimeter of FRP strips are different, it is better to evaluate the overall relaxation pertaining to confining pressure. The quantities of relaxations illustrated in figure 5 are higher than the amounts that were published previously by other researches [5] [6]. According to the research conducted by *Patrick X. W. Zou* the relaxation of carbon fiber is less than 1% after 1000 hours of loading [5]. But the relaxation quantities of carbon fabrics in this research are much higher than 1%. The most important reason of this difference is the damage, which occurs for fibers or precured FRP during the pre-stressing, and in the first hours of relaxation tests. The relaxation reported by other researches mostly is due to one fiber not fabric. But in this research the relaxation of fabrics containing million fibers were investigated. It is very difficult to pre-stress the million of fibers equally while we are pre-stressing a bunch of fibers. In these cases some of the fibers stretch less and others more than the mean strain. Because the lack of uniform stresses distribution between fibers, some of fibers would be torn and consequently the section area of fabric and stretching load would be reduced. This issue was proved by the sounds that were heard during the first hours of tests, indicating the tearing of fibers and the microscopic observation of strips after the tests.

The high amounts of damage in Sq-Sim and C-Sim specimens were because of the friction of column surfaces and their effects on damage of fibers. Unpromising effect of pre-stressed CFRP strips in the research conducted by *Nasrolahzadeh et al* is due to the damages that have occurred during the pre-stressing. In that research, the carbon fibers were pre-stressed 2500 μs in the corners, which corresponds with Sq-Sim-CFRP specimen. But the performances, strength and ductility of columns retrofitted with passive confinement were equal or a little better than columns retrofitted with pre-stressed strips. At first, the pre-stressing level is very little because more damages may occur in higher levels. Moreover, the damages reduce the effects of CFRP strips after pre-stressing so the efficiency of active confinement in this case is less than passive confinement. For precured CFRP and AFRP strips the amount of damages are less than carbon and aramid fabrics. This is because of the role of matrix to transfer the shear stress, which appeared in the precured strips. In precured FRP composites during initial stressing, the matrix carries a portion of the load. Over time, this load will be carried completely by the fibers. This is because of relaxation of matrix and time-dependent shear moduli of it. As mentioned earlier the fibers in the matrix of precured FRP systems are not perfectly aligned. So straightening of fibers due to their stresses is also conductive to stress relaxation for precured FRP materials.

Table 2 presents the key results of the tests. The pre-stressing level indicates the diagonal confining load for specimens. The amounts of pre-stressing of Sq-Sim-AFRP tests are corresponding with the research conducted by Yamakawa et al 2001. They proposed 7000 Micro strain as an optimized pre-stressing strain at the corner of specimens. This strain was captured at Sq-Sim-$AFRP_2$ with 11.68 KN confining pressure. In Sq-Sim-$AFRP_1$ and Sq-Sim-$AFRP_3$ 4000 and 10000 Micro strains were captured at the corners to correspond other tests of that research, too. Sq-Sim-$CFRP_1$ simulate the relaxation for 2500 Micro strain which was selected as corner strain in the research conducted by Nasrollahzadeh et al 2005. Sq-Sim-$CFRP_2$ with approximately 5700 micro strains was the maximum amount of pre-stressing which were applied to CFRP strips before damage. Over than this strain the tearing of fibers in FRP strips started. For C-Sim tests approximately equal amount of confining pressure was applied for both CFRP and AFRP strips to compare the amounts of relaxation. The pre-stressing level achieved in ExGrout-Sim tests were not under control and depended to the expansion of expansive grout. The strain measured for CFRP and GFRP in these tests were approximately 1200 and 2100 micro strain respectively.

Table 2 Summary of test results

Test type	Pre-stressing level (KN)	Relaxation after 48 hours		Relaxation after 1000 hours	
Sq-Sim-$AFRP_1$	6.94	5.90	14.90%	5.36	22.70%
Sq-Sim-$AFRP_2$	11.68	9.90	15.20%	9.00	22.90%
Sq-Sim-$AFRP_3$	17.32	14.60	15.70%	13.30	23.20%
Sq-Sim-$CFRP_1$	3.49	3.33	4.5%	3.27	6.3%
Sq-Sim-$CFRP_2$	7.84	7.43	5.20%	7.28	7.10%
C-Sim-AFRP	5.48	4.54	17.20%	4.34	20.80%
C-Sim-CFRP	5.55	5.32	4.10%	5.18	6.70%
ExGrout-Sim-CFRP	15.70	14.80	5.70%	13.78	12.20%
ExGrout-Sim-GFRP	12.37	10.70	13.50%	10.50	15.10%

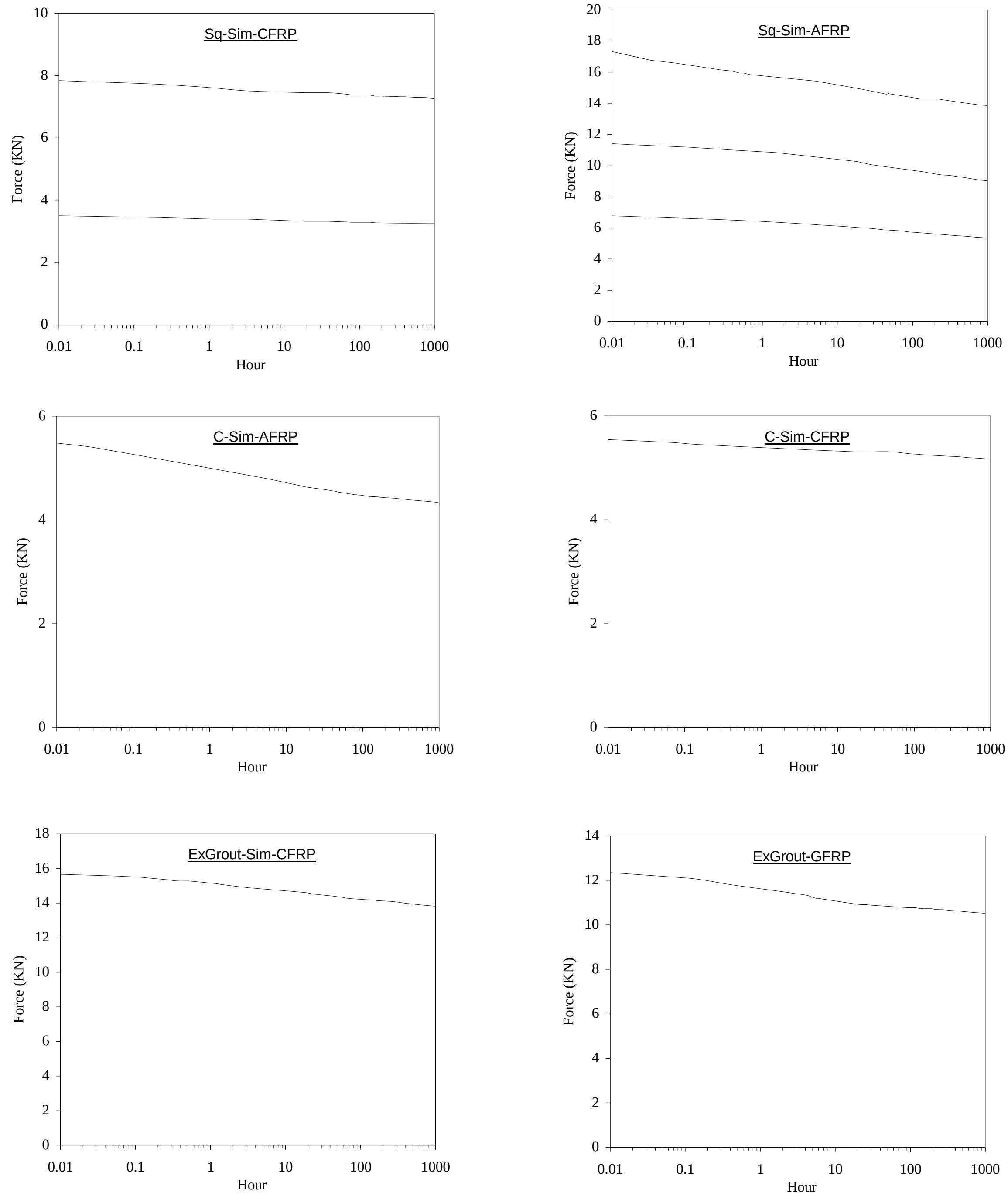

Fig. 5 Relaxation of FRP materials for first three test setups

3.2 Effect of fiber types

Table 2 shows higher amounts of relaxation for aramid fabrics against carbon and glass. As mentioned earlier the viscoelastic behavior of most composites, is primarily due to the matrix so composite materials are reinforced with fibers to resist relaxation. But aramid fibers exhibit a viscoelastic behavior itself and show significant decrease in tensile strength during the time when they are subjected to constant load. The other reason of higher aramid relaxation in this research against carbon and glass ones is due to the woven pattern of it. For unidirectional carbon fabrics which were used in this research 100% of fibers are in longitudinal direction but the aramid fibers are not in one direction. So after stretching the microscopic motion occur between fibers to become straight. Carbon fibers have nearly no viscoelastic behavior but the damage and fiber tearing in carbon fabrics are more than glass and aramid.

Figure 6 show the relaxation plot of C-Sim-AFRP and C-Sim-CFRP. The pre-stressing levels of these specimens were selected nearly constant deliberately. But the relaxation of AFRP strip is approximately 14% more than CFRP.

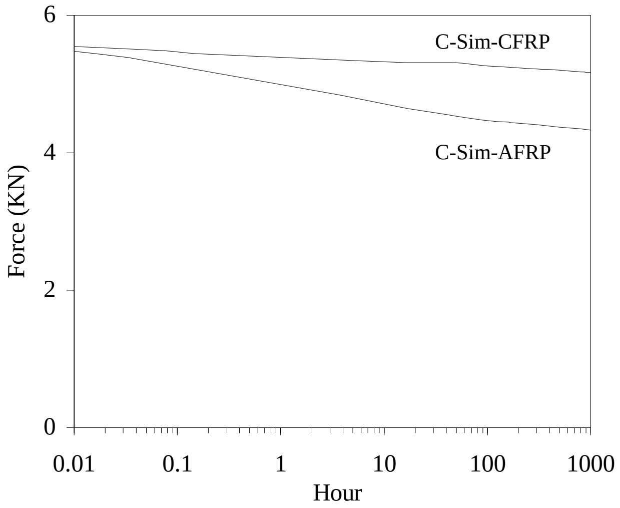

Fig. 6 Relaxation plot of C-Sim-AFRP and C-Sim-CFRP

3.2 Effect of size

In general the real strengths of materials are less than their theoretical strength. This is because of the imperfections that the materials may contain. If the lengths and the volumes of materials become larger, the amounts of probable imperfections will be certainly higher. So it is reasonable for specimens with more volumes to have less strength. This is the base of statistical features of material failures. This issue occurred in our research by testing the specimens with different lengths. The relaxations of longer and wider strips were more than shorter and thinner specimens. In larger strips the distribution of stresses between fibers are more irregular than smaller ones, so the probable tearing is more. Specimens Sq_2-Sim-AFRP and Sq_2-Sim-CFRP were pre-stressed around square specimen with 50 cm width and the length of these strips were twice than other Sq specimens. Fig 7 shows the relaxation plots of Sq_2-Sim-AFRP, Sq_2-Sim-CFRP, Sq-Sim-$AFRP_3$ and Sq-Sim-$CFRP_2$.

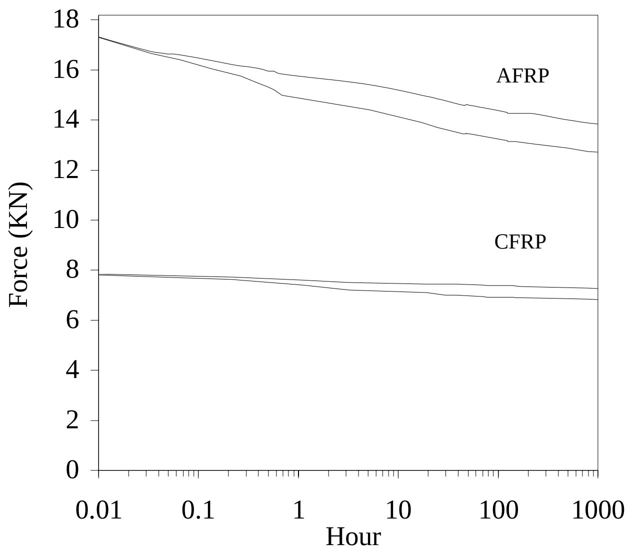

Fig. 7 Relaxation plot of AFRP and CFRP strips with different sizes

The pre-stressing loads of CFRP specimens and AFRP ones were selected constant to clear the effect of size in relaxation. The relaxation of Sq_2-Sim-AFRP is nearly 26.5% which is 3.5% more than Sq-Sim-$AFRP_3$. For carbon strips the increase in relaxation is more than aramid strips. The relaxation of Sq_2-Sim-CFRP and Sq-Sim-$CFRP_2$ are 12.5% and 7.1% respectively. The amounts of relaxation for specimens with different lengths are equal theoretically. But more faults and imperfections in larger specimens are conductive to more stress relaxation. If we consider S (V) the probable of existing faults in an specimen with V volume, the probable of existing faults in an specimen with XV volume is $S (V)^X$. As mentioned earlier the probable tearing for carbon strips is more than aramid strips during pre-stressing. So increase in relaxation for carbon specimens with larger volume are more than aramid. The sizes of FRP materials should be considered as an effective parameter in the relaxation.

4 CONCLUSION

- One of the most salient problems in pre-stressing the FRP composites is stress relaxation, which pertains to the decrease in the stresses while the deformation is held constant.
- Relaxation of FRP materials not only are due to resin matrix, straightening of fibers and relaxation of fibers, but are also related to level of pre-stressing, types of fibers, anchorage systems, and sizes of specimens.
- The least relaxation was observed for CFRP materials and the most relaxation was observed for AFRP materials. This is because of viscoelastic behaviour of aramid materials. The most reason of CFRP relaxation in pre-stressing tests is due to tearing of carbon fibers during the tests.
- Reduction of strain measured by strain gages during the relaxation tests are due to different resistance of strain gages in time, relaxation of resins used to install the gages and relaxation pertaining to the screwing system.
- The effect of sizes for FRP specimens is one of the important parameters in relaxation. In specimens with larger volumes, the amounts of imperfection, tearing during the tests, none straightening of fibers and different thickness in saturated fabrics are more than smaller ones.
- More investigations are needed to capture a relaxation formula for FRP materials including following parameters: fiber types, level of pre-stressing, anchorage systems, size of FRP materials, temperature and humidity.

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