Innovative Mechanical Device for the Post-tensioning of Glass Fiber Reinforced Polymer Bars for Masonry Type Retrofit Applications

by P. Yu, P.F. Silva and A. Nanni

ABSTRACT—A mechanical device specially designed for the application of low-level post-tensioning forces to glass fiber reinforced polymer (GFRP) bars has been developed at the University of Missouri-Rolla. Some of the advantageous features of this device are that it is simple to assemble and the low-level post-tensioning forces can be applied manually and safely without the need for hydraulic jacks or heavy equipment. This device has been conceived with the main objective of retrofitting masonry buildings, some of which remain in service despite large, open cracks leading to considerable instability and serviceability concerns. According to the method derived in this paper, GFRP bars are installed in artificially imposed grooves and then post-tensioned with low-level stresses with the main objective to partially close these cracks, such that the serviceability and in-plane capacity of un-reinforced masonry (URM) buildings may be regained. In this paper we describe the mechanical components of this device, along with its advantageous features and potential application for the retrofit of URM walls.

KEY WORDS—Anchorage, GFRP bar, masonry wall, post-tensioning, prestressing, thermoplastics

Introduction

In their present forms, traditional methods for post-tensioning and anchorage of steel tendons cannot be used directly for fiber reinforced polymer (FRP) bars because of difficulties associated with the gripping of FRP bars in the anchorage region. These may include damage to the FRP bars due to excessive gripping force and/or slippage of the bars out of the anchorage zone caused by low friction between the gripping mechanism and the bars. A variety of anchorage systems have been recently developed to address the poor performance of the anchorage of FRP bars.[1–6] These can be divided into three general groups: wedge, resin/grout potted, and spike systems. These systems have inevitable drawbacks in practice, such as potential for local damage to the FRP bars, curing time for resin, field setup time, and special requirement for the bars, among many others. A hand-held device was developed in this research program to address some of these issues. This device features a simple way to simultaneously anchor and apply low-level tensile forces to glass fiber reinforced polymer (GFRP) bars without causing damage to the bars due to creep-rupture. Furthermore, this device can be reused for future applications.

In this system, the mechanism used for the anchorage of GFRP bars was developed based on the property of thermoplastic resin, inherent to the GFRP bars produced for use with this particular device.[7,8] Thermoplastic resins were considered for this type of application because when they are reheated they become soft, and may be remolded as necessary to achieve the desired anchorage system. In addition, it can be shown that no permanent damage is caused to the bars.

Based on this property, the GFRP bars are reheated by controlling the temperature and, after the resin is softened, a wedge or a nail is driven into the center of the bars from each end to create the desired anchorage mechanism. Thus, by combining the resin's thermoplastic property with this specially designed device, low-level tensile forces may be applied to GFRP bars with the main goals of increasing un-reinforced masonry (URM) wall strength and restoring the serviceability by closure of cracks from stressing the bars placed in artificially imposed grooves.

The mechanical components of this device, assemblage, and potential application for the retrofit of URM walls are discussed in this paper.

Device Description

Features

Experimental results have proven that this new hand-held device features the following characteristics.

1. Because it is a hand-held device, a hydraulic jack is not needed for stressing of the GFRP bars, which is one of the most significant features of this device.
2. This device can be used within tight spaces.
3. It can be easily transported and handled.
4. It is cost effective, because it can be reused to post-tension other bars without any limitations.

According to these beneficial features, a group of only two technicians is required to assemble and work with this device to effectively retrofit masonry walls with GFRP bars.

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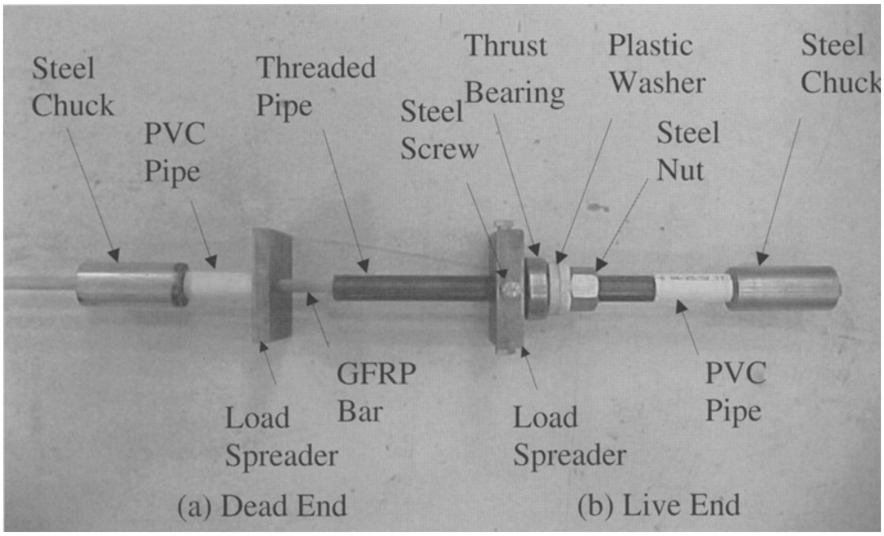

Fig. 1—Hand-held device components

Main Components

The main components of this device are shown in Fig. 1 and may be divided into two ends.

I. Live End

This consists of the following components and corresponding functions.

- (i) A wedge or nail, inserted in the end of pre-heat-softened GFRP bars (see Fig. 2), creates the appropriate anchorage mechanism (see Fig. 3).
- (ii) A steel chuck (with steel wedges inside), commercially available from the prestressing industry, is placed around the end of the deformed bars for gripping (see Fig. 1).
- (iii) A PVC pipe, placed before the steel chucks, allows for easy cutting of the GFRP bars with a grinder/hand-held saw after the resin has cured. This is a necessary component to remove the device after the bars are fully bonded to structures.
- (iv) A threaded pipe, constructed with four grooves cut parallel to its longitudinal axis and held in place by a load spreader and steel screws, prevents the pipe and GFRP bars from twisting during stressing. This prevents the bars from being damaged during stressing.
- (v) A steel nut, placed on the threaded pipe, is used to apply the tensile force manually with a wrench.
- (vi) Plastic washers, placed between the steel nut and the thrust bearing, helps in further reducing friction.
- (vii) A thrust bearing, commercially available, is mainly used to further decrease friction between the steel nut and the load spreader.
- (viii) A load spreader, screwed in place with four screws to the threaded pipe, prevents twisting of the pipe. This component also reduces the bearing stresses on the structure.
- (ix) Four steel screws, specially designed with smooth unthreaded ends, allow easy sliding of the threaded pipe during stressing through the load spreader.

II. Dead End

At the dead end the device consists only of a wedge or a nail, a steel chuck, a PVC pipe, and a load spreader, which are identical to the live end, to the exception of the load spreader as no screws are required to prevent twisting.

In the next section, the necessary steps to accomplish the assemblage and operation of this device are described.

Assemblage

The first step in the assemblage of the hand-held device consists of providing anchorages at the ends of the GFRP bars by using a wedge or nail. Because of the excellent thermoplastic property of these bars, the ends of the bars can be softened using a rope heater (see Fig. 2). With the help of a temperature controller, the surface temperature of the bars can be maintained close to the glass transition temperature. After the ends are softened, a nail or wedge is manually inserted to create a slight expansion, critical for anchorage to the steel chucks (see Fig. 3). The anchorage between the bars and the steel chucks is achieved through mechanical interlock to the steel wedges, which are placed inside the steel chucks. In addition, experimental investigation has shown that no permanent damage is caused to the bars during stressing, because only low-level stresses are required.

After the anchorage mechanism is created, the system is assembled according to the setup shown in Fig. 1. A key issue is that the threaded pipe should be prevented from twisting to avoid causing damage to the GFRP bars. This is accomplished by placing steel screws with smooth unthreaded ends through

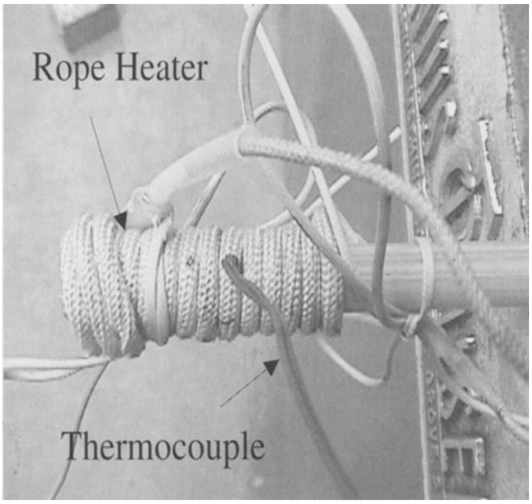

Fig. 2—Heating of a GFRP bar

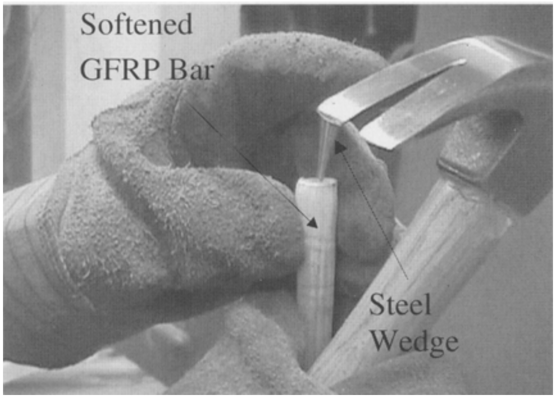

Fig. 3—Inserting steel wedge in a GFRP bar

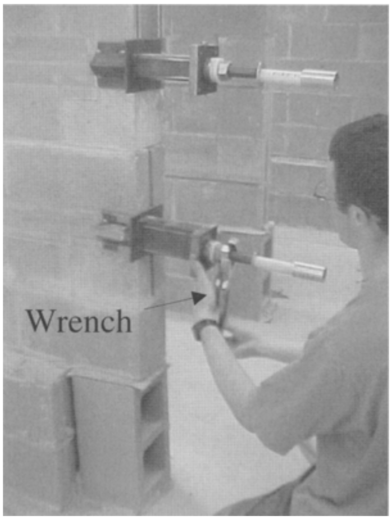

Fig. 4—Manually stressing a GFRP bar with a wrench

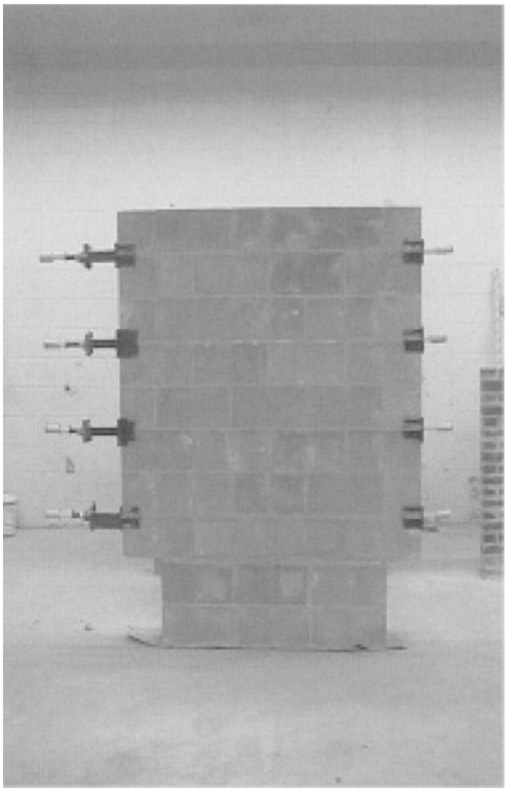

Fig. 5—Assembled system in a masonry wall

the load spreader. The bars can then be bonded to the structures by adopting the retrofit technique designated in the literature as near surface mounted (NSM) strengthening.[9,10] According to this technique, the bars are placed inside grooves previously made on the surface of the member being strengthened. In this type of application, either horizontal or vertical grooves are cut and cleaned in the masonry walls before operation.

In the next step, resin is placed inside the grooves and the system is put in place. The system is then fixed to the structure by tightening the steel nut in the live end with a regular wrench, as shown in Fig. 4. Using a calibrated torque wrench, strain gages installed in the bar, and/or a load cell positioned at either end, the applied load is controlled to the desired level or until closure of the cracks is achieved. The complete assembled system is depicted in Fig. 5 where four bars are placed in horizontal grooves.

Finally, when the resin inside the grooves is properly cured, which usually occurs within 24 h, the GFRP bars are cut through the PVC pipes (see Figs. 1 and 4) and the device is removed for further applications. This system was experimentally investigated in the laboratory at the component and system level and results are presented in the next section.

The size of steel wedges or nails and quality of expansion are key issues for the reliability of the anchorage mechanism. The wedge or nail needs to be smoothly inserted to the center of the ends of GFRP bars and fully covered by the bars. The mechanism may fail before desired force could be achieved if a wedge or nail of too small size is used, or ideal expansion is not achieved.

Experimental Evaluation

The experimental investigation was performed in two phases.[8] These two phases are described next.

Phase I: Component Characterization

The system was first evaluated with Ø6 and Ø13 GFRP bars in the laboratory according to the test setup shown in

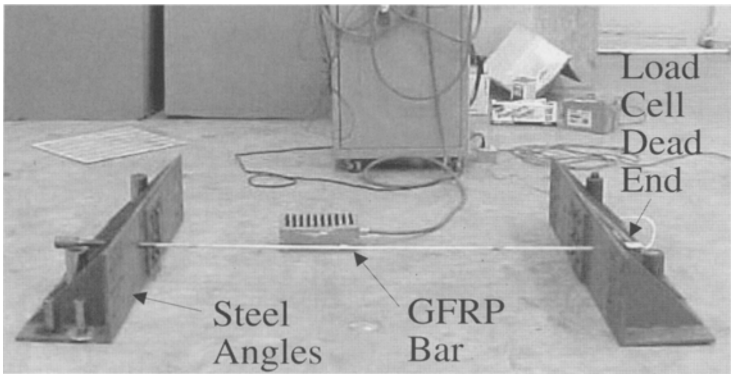

Fig. 6—Test setup for component evaluation

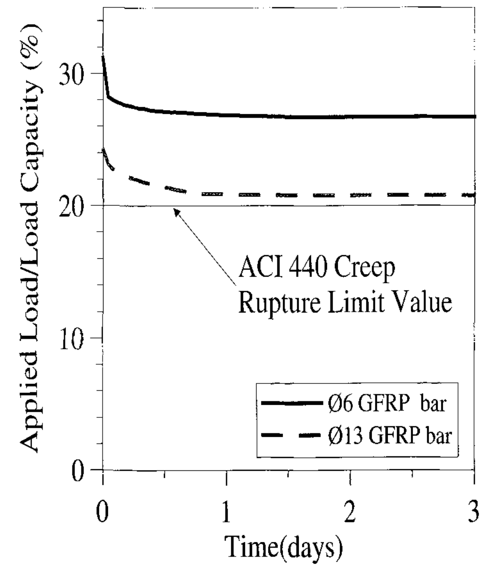

Fig. 7—Load relaxation of GFRP bars

Fig. 6. Steel chucks with internal wedges, with diameters of 8 and 16 mm respectively, were used. The main objectives of this phase were (1) to explore the ease of installation, and (2) to determine stress losses. As shown in Fig. 6, the post-tensioning system was evaluated by installing the system between two steel angles, which were fixed to the ground by means of tie-downs. Holes were drilled into the steel angles in order for the GFRP bars to pass through. A load cell placed at the dead end and connected to a data acquisition system was used to measure the applied load, which was achieved by tightening the steel nut at the live end and outside the steel angles. The bars were stressed under a sustained loading for three days and stress losses due to bar relaxation and anchorage losses were recorded during this period.

The measured tensile strengths of the tested GFRP bars were 1020 and 689 MPa for the Ø6 and Ø13 bars, respectively (Table 1). Test results presented in Fig. 7 show that after only one day the stress in the bars stabilized at approximately 85% of the initially applied stress for both Ø6 and Ø13 bars. The registered load levels after three days were higher than the limit of $0.20 f_{fu}$ imposed by ACI-440,[11] which is used to prevent creep-rupture of GFRP bars.

Creep-rupture is a critical issue in the application of FRP materials, especially in the case of GFRP bars. According to ACI-440, after consideration of a long-term environmental factor, the stress limit for a GFRP bar is $0.2 f_{fu}$, where f_{fu} is the design strength and derived from the guaranteed tensile strength modified by a knock-down coefficient to account for environmental effects. Therefore, in the retrofit of masonry walls using prestressed GFRP bars, consideration must be given to the creep-rupture limit, because in these applications the bars are subjected to sustained loading after prestressing. As such, the prestress level should not exceed the creep-rupture limit. Since in these types of applications the desired prestress levels are below $0.20 f_{fu}$, creep-rupture is not an issue in this research program. However, it is important to note that this system can post-tension GFRP bars to prestress levels higher than $0.2 f_{fu}$, as shown in Fig. 7. In addition, low-level prestressing with the low modulus of the GFRP bars is highly suitable for masonry retrofit applications. In particular, the low modulus of GFRP bars allows displacements in the masonry with low levels of prestress losses.

All of these indicate that this post-tensioning system can reliably be used to apply low tensile forces to retrofit masonry walls without incurring significant stress losses due to bar relaxation and anchorage losses within stress levels that are limited by ACI 440 specifications.

Phase II: Retrofit Applications to Masonry Walls

This system has also been successfully used in laboratory conditions to stress masonry walls with the main objective of increasing their in-plane load capacity. Future tests will concentrate on studying the feasibility of this system to perform closure of existing cracks. The laboratory test setup to study the in-plane response of these walls is depicted in Fig. 8, where it is shown that a total of seven prestressed NSM bars were used.

The bars were bonded to the URM walls according to the NSM method and stressed in place. Next, the bars were cut through the PVC pipes (see Fig. 1). Transfer occurred at approximately 48 h after stressing (1) to allow for the resin to properly cure, and (2) to reduce further stress losses due to the elastic shortening of the resin. After strengthening, the masonry walls were tested under monotonically increasing load up to failure. Two hydraulic jacks connected in parallel to a manual pump and positioned at one corner of the walls were used to apply the desired load, as shown in Fig. 8. During testing, the hydraulic jacks transmitted the load to the walls by two steel shoes at diagonal corners in order to reduce concentrated damage at the corners.

A total of four walls were tested to evaluate this device application to the strengthening of masonry walls. The specimens had a nominal dimension of 1.60 m^2 and a thickness of 152 mm. The test matrix is presented in Table 2. Wall A was constructed with no retrofit scheme and was used as the control unit to establish a baseline for performance. The remaining tested walls were strengthened with Ø6 GFRP bars stressed to percentage of levels to ultimate capacity as indicated in Table 2. For ease of comparing test results, these stress levels were normalized according to

$$nf \frac{f_{fv}}{f'_m} \frac{A_f}{A_w} \tag{1}$$

where n is the number of GFRP bars, f is the percentage of

TABLE 1—MATERIAL PROPERTIES

	Tensile strength (MPa)	Compressive strength (MPa)	Elastic modulus (GPa)
Ø6 GFRP bar	1024	–	157
Ø13 GFRP bar	689	–	150
Masonry prism	–	17	15

TABLE 2—TEST RESULTS OF MASONRY WALLS

Walls	A	B	C	D
Quantity of Ø6 GFRP bars	None	2	3	7
Stressing level of bars (%)	0	44.0	21.6	19.8
Normalized stress (%) (see eq (1))	0.00	0.66	0.48	1.04
Load at failure (kN)	108	196	211	235

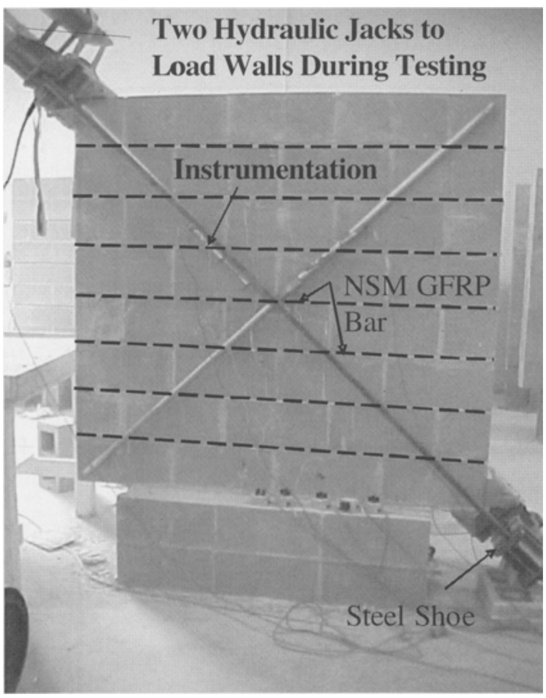

Fig. 8—Testing of retrofitted masonry walls with prestressed NSM GFRP bars

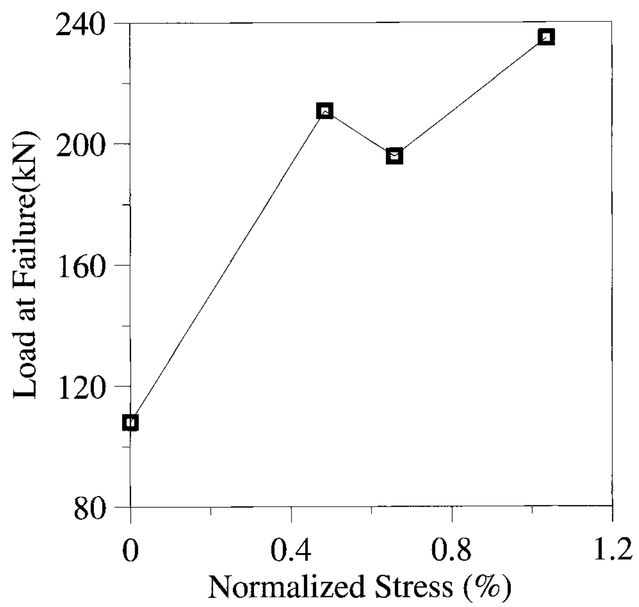

Fig. 9—Masonry walls test results

stress level to the ultimate capacity, f_{fv} and A_f are the tensile strength and cross-sectional area of the bars respectively, and f'_m and A_w are the compressive strength of masonry prisms and the vertical face area of the masonry walls against which the bars were stressed.

Each of the retrofitted walls was selected with the primary goal of comparing the increase in capacity as the number of bars increased and prestress level changed. Table 2 also shows the number of bars used in the strengthening of each wall and failure loads. In Fig. 9 the failure loads are plotted as a function of the normalized stress computed according to eq (1). It is clear that the load at failure was increased as the normalized stress increased. In all tested walls, failure can be characterized by a brittle mode through the development of large diagonal cracks that occurred mainly along the diagonal compression strut. Future research will concentrate on the application of this device to the retrofit of existing buildings, with the main goal of exploring in further detail the features of this device previously described.

Conclusions

In this paper we have discussed a mechanical device especially designed for the application of low-level post-tensioning forces to GFRP bars. Conclusions drawn from this research program are as follows.

1. The device is capable of anchoring and applying low-level tensile forces to GFRP bars. Test results at the component level show that after only one day the stress in the bars stabilized at approximately 85% of the initially applied stress.
2. No permanent damage was caused to the bars resulting from the reheating of the bars to develop the appropriate anchorage mechanism.

3. This hand-held device is simple to implement in the retrofit of masonry walls, and can be easily reused after many applications.
4. The system is practical for the retrofit of masonry walls though the application of low-level tensile forces.
5. Increase in the in-plane capacity of masonry walls can be achieved by providing GFRP bars through the NSM technique and also by applying low-level prestressing forces to these bars.

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