FRP COMPOSITES AS AN ALTERNATIVE MATERIAL TO STRENGTHEN, UPGRADE AND REPAIR INFRASTRUCTURE

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ABSTRACT

The major part of the infrastructure components of Saudi Arabia was built in the last 30 years and the cost was hundreds of billions of Saudi Riyals. Unfortunately, a large part of that infrastructure was built in the absence of local design codes that consider the influence of local conditions, adequate supervision and lack of quality control. Therefore, a significant part of the beautifully constructed structures is now suffering from an accelerated deterioration. This was further aggravated by the severe weather of the country.

As part of the effort in evaluating the suitability of the available alternatives to increase the span life of the infrastructure, several research projects were funded by several governmental agencies. This paper presents some details about a project that was funded to investigate the suitability of using fiber-reinforced polymer composites to repair, strengthen and/or upgrade beams, columns, walls and pipes.

Keywords: *FRP sheets, composites, flexural members, columns, walls, pipes, external reinforcement.*

الملخص

لقد تم تشييد الجزء الأعظم من مكونات البنية الأساسية في المملكة العربية السعودية خلال الثلاثين سنة الماضية وبتكلفة بلغت مئات عدة من بلايين الريالات. ولكن ولسوء الحظ فإن جزء كبير من تلك البنية الأساسية قد تم بناؤها في غياب نظم التصميم المحلية التي تعتبر ظروف التشغيل الفعلية وبغياب الإشراف الكافي وعدم وجود دقة في الجودة النوعية. ولهذا فإن جزءاً كبيراً من البنية الأساسية تعاني اليوم من تدهور متسارع وقد زاد في ذلك الظروف الجوية القاسية في المملكة.

وكجزء من الجهد الموجه لتقييم ملاءمة البدائل المتوفرة لإطالة العمر التشغيلي للبنية الأساسية فقد تم تمويل عدة مشاريع بحثية في هذا المجال من قبل المؤسسات الحكومية. وتقدم هذه الورقة بعض المعلومات التفصيلية عن أحد المشاريع الكبيرة والتي تم تمويلها لدراسة مدى ملاءمة صفائح المواد المركبة لإصلاح وتقوية ورفع كفاءة العوارض والأعمدة والحوائط والأنابيب.

1. INTRODUCTION

A large part of the infrastructure of Saudi Arabia, although it is relatively new, is suffering from different types of deteriorations. This is particularly the case in coastal areas where the rate of deterioration is aggravated by the combined effect of hot weather and high relative humidity. Thus, there is an urgent need to repair and strengthen the existing infrastructure. On account of this, many research groups in the country have focused on this problem. Recently, significant research effort has been carried out on the numerous aspects related to the use of composite materials for structural rehabilitation. Among the research topics considered is the one concerned with in this paper. It had the title “Rehabilitation of the infrastructure using composite fabrics” [Alsayed et al., 2002]. The following tasks were carried out as part of the research project.

Task 1	Flexural behavior of concrete beams retrofitted with epoxy bonded FRP sheets
Task 2	Shear behavior of concrete beams retrofitted with epoxy bonded FRP sheets.
Task 3	Strength of concrete columns retrofitted with high strength composite Sheets
Task 4	Durability of concrete beams strengthened with epoxy bonded FRP sheets.
Task 5	Strength tests for unreinforced masonry walls retrofitted with composite materials.
Task 6	Strength tests for pipes retrofitted with composite sheets

Some details about what has been done in each task and the main conclusions are presented next.

2. FLEXURAL BEHAVIOR OF CONCRETE BEAMS RETROFITTED WITH EPOXY-BONDED FRP SHEETS

The effectiveness of FRP bonding at the tension side of flexural members in increasing the flexural capacity of RC beams have been previously reported. The technique has also been successfully applied in the field in many parts of the world. Some of the factors that influence the effectiveness of FRP bonding include: reinforcement ratio, ultimate strength of concrete, material type of FRP sheet, width to thickness ratio of the sheet, initial strains on the beam and end anchorage of the sheets [Spadea et al., 1997, Matthys and Taerwe, 2000].

In this study, several series of beams retrofitted with glass-FRP (GFRP) or carbon-FRP (CFRP) were cast and tested. The variables considered in the study include the type of FRP materials, the number of layers used in strengthening, the shape of strengthening (flat versus U-shape) and the level of loading at the time of strengthening. Test setup of the some specimens is presented in Fig. 1. The load deflection relationships for the same specimens are shown in Fig. 2.

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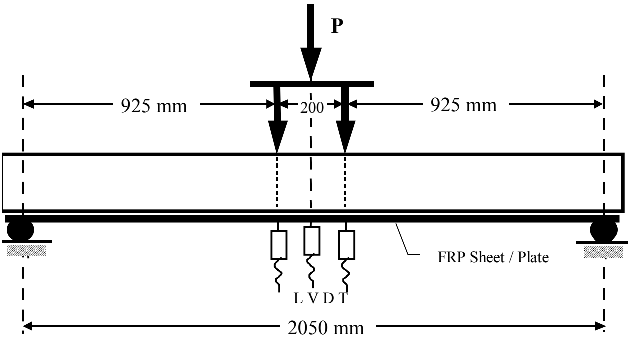

Figure 1: The test setup for flexural specimens

The effects of using FRP sheets in increasing the flexural strength and flexural rigidity are quite obvious in the results presented in the figure. The results also show that the benefit of using the FRP sheets increased as the number of layers increased from one to two. In fact, after retrofitting, the flexural capacity for some beams, with some special details, increased by more than 100% of their original strength.

The moment capacity corresponding to classical modes of failure can be evaluated on the basis of conventional procedure recommended by the ACI 318 Code assuming that, in addition to conventional assumptions, full bond between concrete and FRP Laminate exists.

The ACI design code procedure states that in order to assure tension failure, the steel reinforcement is assumed to have a strain, ε_s, greater than the yield strain of the steel, ε_y. The internal force components acting on a rectangular RC beam section strengthened with FRP Laminates are the compressive force in concrete, C, the tensile force in steel reinforcement, T_s, and the tensile force in the FRP Laminate, T_p. The section is assumed to have a linear strain distribution. From the equilibrium of internal forces, a quadratic equation is obtained as a function of the depth of neutral axis , c , which leads to the nominal moment capacity, M_n, when taking the moment about the line at which the concrete compression force acts:

$$M_n = A_s f_y \left(d - \frac{a}{2} \right) + A_p f_p \left(h - \frac{a}{2} \right) \tag{1}$$

where, $a = \beta_1 c$, $f_p = E_p \varepsilon_p$, d is the distance from extreme compression fiber to centroid of tension reinforcement, A_s is the area of tension steel reinforcement, A_p is the area of FRP Laminate, f_y is the yield stress of steel reinforcement, f_p is the tensile stress in the FRP Laminate, E_p is the modulus of elasticity of FRP Laminate, and ε_p is the strain in the FRP Laminate, corresponding to f_p. The thickness of adhesive and Laminate is very small as compared to the beam depth so that they are ignored in formulation of Eq. (1).

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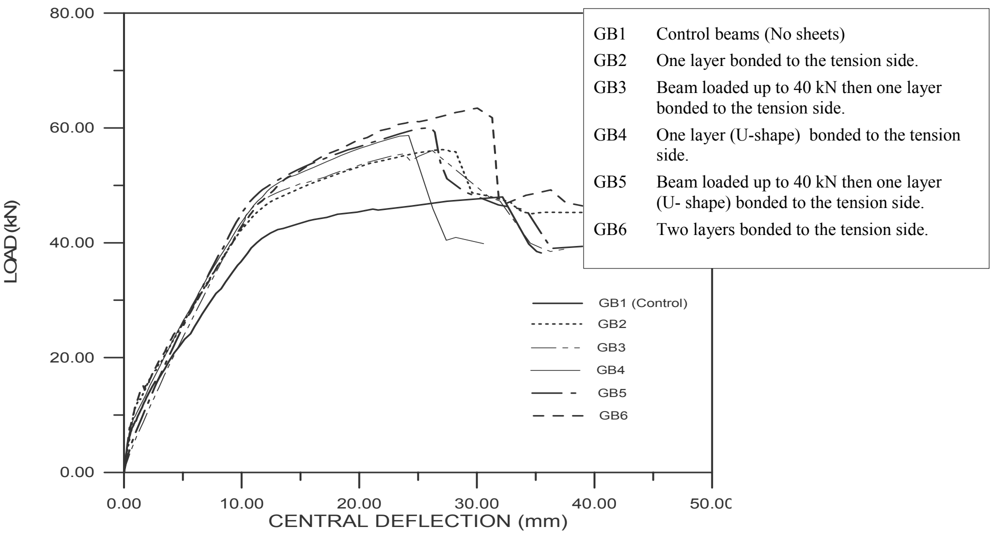

Figure 2: Load-deflection relationship for the second series of specimens

3. SHEAR BEHAVIOR OF CONCRETE BEAMS RETROFITTED WITH EPOXY-BONDED FRP SHEETS

A large number of investigation has been carried out to explore the use of FRP fabrics for flexural strengthening of beams. It is confirmed that use of FRP fabric is an effective means of strengthening of reinforced concrete (RC) members. However, a relatively limited investigations have been carried out on the shear behavior of RC beams with externally bonded FRP fabrics. Conventionally, the design codes consider the shear resistance of a RC beam as the sum of shear resistance of concrete and the web reinforcements. The concrete contribution comprises aggregate interlock and the dowel action of flexural reinforcement. Since the FRP materials behave differently than steel, the contribution of FRP materials need to be included carefully in the design equations on the basis of detailed experimental evaluation.

In this work, several series of experiments were carried out to investigate the contribution of the FRP sheets in carrying shear stresses. The variables considered in the tests were the FRP material type, direction, location and method of using the sheets to resist the shear stresses. A significant improvement in the shear capacity is achieved by using FRP sheets along the sides and the tension face of the beam (U-shape sheet). Among all the configurations considered, continuous U-shape CFRP provided the best shear resistance, even if the beams were cracked prior to applying the sheets. Some details and test setup used for the first series of test specimens are presented in Figs. 3. The load deflection relationships, also for the same series, are presented in Fig. 4. The results reveal a significant enhancement in the shear carrying capacity of the beam due to the epoxy bonded FRP sheet.

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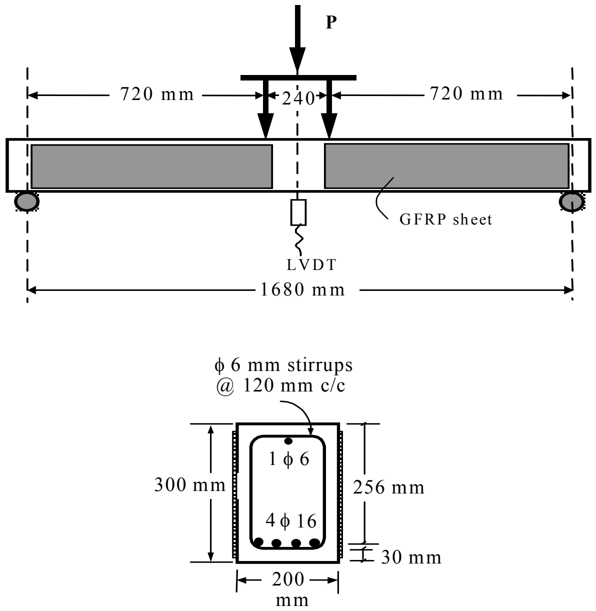

Figure 3: The beam set-up and its cross-section for shear testing. *(First Series)*

In addition to the experimental tests, most of the available analytical models suggested to predict the contribution of FRP sheets in carrying shear stresses were reviewed. Their accuracy in predicting the experimental results obtained in this study as well as those available in the literature were evaluated. It is found that, of the models considered in this comparison, the model suggested by Triantafillou and Antonopoulos [1999], though it is simple, provides a reasonable prediction of the measured values. It is given as:

$$V_{nf} = \frac{\varepsilon_{fe,A} E_f A_f d(\sin\beta + \cos\beta)}{s_f} \tag{2}$$

Where $\varepsilon_{fe,A}$ is the effective FRP strain at failure = $0.9\varepsilon_{fe} \leq \varepsilon_{max} = 0.006$, A_f is the area of FRP shear reinforcement =2 $t_f\, w_f$, d is the depth of FRP (usually depth of beam), β is the angle between FRP orientation and the axis of the beam, and s_f is the spacing of FRP strip. The ultimate shear capacity is :

$$V_{uf} = \phi V_{nf} \tag{3}$$

where, $\phi = 0.8$ for fracture and $0.9\varepsilon_{fe} < \varepsilon_{max}$, $\phi = 0.75$ for debonding and $0.9\varepsilon_{fe} < \varepsilon_{max}$, and $\phi = 0.75$ for $0.9\varepsilon_{fe} = \varepsilon_{max}$

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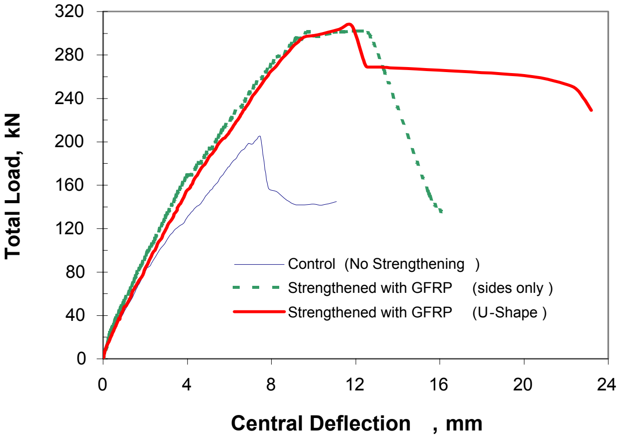

Figure 4: The shear load versus central deflection for the three groups

4. STRENGTH OF CONCRETE COLUMNS RETROFITTED WITH HIGH STRENGTH COMPOSITE SHEETS

In the early stage, steel jacketing has been proved to be an acceptable technique to retrofit bridge columns to increase strength and ductility as required for seismic demands [Swamy and Gaul, 1996]. The structural effectiveness of this technique has been demonstrated by the observed excellent performance of steel jacketed bridge columns [Swamy and Gaul, 1996]. However, use of composites to retrofit the columns seems to be more effective than using steel plate. It is reported [Xiao, 1998] that, based on actual construction time, approximately 2 hours are sufficient for retrofitting an 8m tall and 914mm diameter column with 4–layer individual shell jackets. Where as, to retrofit the same using steel jackets, 3 to 4 days are needed and steel jacketing system also requires the service of highly skilled welders and crane operators.

In this study, two series of column specimens were cast and tested to investigate the effect of composite jacketing on the overall behavior of the columns and, in particular, on the different expected modes of failure of the columns, which include shear failure, confinement failure and lap splice failure. The main variables in the investigation include column size, FRP material type and number of FRP layers. Furthermore, the available design equation for columns confined with FRP fabrics were reviewed and some modifications of some of the models are suggested to improve their accuracy of prediction.

The first series of the specimens had a cross section of 150×150 mm and a height of 1200 mm. The second series had 300×300 mm cross-section and a total height of 2005 mm.

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The ends of the columns (368 mm each) for the second series of specimens were tapered to eliminate the effect of stress concentration at the ends. Fig. 5 shows a typical specimen from the second series while testing. Both series have indicated that wrapping the columns with FRP sheets greatly improves their ductility. The improvement is very much related to the number of layers and the material type. The load-axial strain in the longitudinal bars at the mid-height of the column is shown in Fig. 6. The improvement in the column capacity and ductility due to the confinement provided by the FRP sheets can be clearly seen in the figure. The contribution of the sheets in enhancing the column response to axial load is expected to be higher for circular columns. This is also confirmed by the results obtained by Pessiki et al. [2001]. This is attributed to the fact that the confinement for the sides of the rectangular columns is not uniform as is the case for the circular columns.

Figure 5. Test setup for column specimen of second series specimens.

4.1. Proposed modified ACI equation for strengthened column

Comparison between the measured and predicted capacity of the columns strengthened with FRP sheets showed that the current ACI models for predicting the column strength cannot be used for reinforced concrete columns confined with FRP sheets. Therefore, some modifications for the ACI models are carried out to account for the presence of the FRP sheets. Further details of the models may be found elsewhere [Alsayed et al., 2002].

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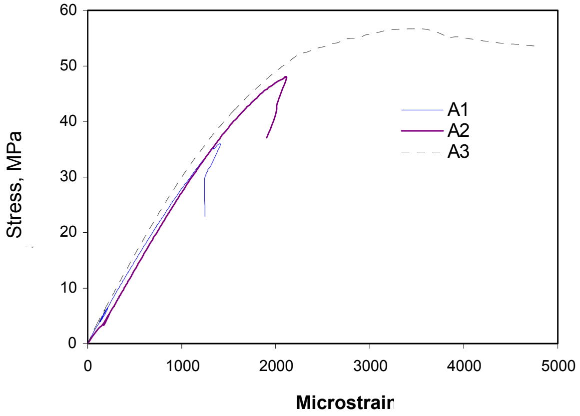

A1	No Strengthening
A2	The ends were wrapped with one layer of CFRP composite sheet of 20 cm width
A3	The whole column was wrapped

Figure 6. Load versus axial strains in the longitudinal bars.

The existing ACI equations for determining the axial load capacity of reinforced concrete column are as follows:

For spirally reinforced column:

$$P_n = 0.85\left[0.85\, f_c^{/}\left(A_g - A_{st}\right) + f_y\, A_{st}\right] \qquad (4)$$

and for tied column:

$$P_n = 0.80\left[0.85\, f_c^{/}\left(A_g - A_{st}\right) + f_y\, A_{st}\right] \qquad (5)$$

These have been modified to include the strengthening effect of confinement with composite fabrics. The strength enhancement portion of the proposed model for ultimate strength of concrete, f'_{cc}, as presented by Alsayed et al {2002] is:

$$f_{cc}^{/} = f_{co}^{/} + \alpha\left[4.0(f_e)^{0.79}\right] \qquad (6)$$

where $f_{cc}^{/}$ is the confined concrete strength, $f_{co}^{/}$ is the unconfined concrete strength, and f_e is the effective confining pressure. In this case, the strength portion of unconfined concrete strength of the ACI design equations is modified. A value of 0.80 is used as reduction factor, α, for the enhanced strength due to confinement. This value is the lower bound of α as proposed in the strength model and can be considered conservative for the design purpose. Thus the suggested modified ACI design equation for spirally reinforced column is:

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$$P_n = 0.85\left[\left\{0.85\, f_c^{/} + 0.80 * 4.0\left(f_e\right)^{0.79}\right\}\left(A_g - A_{st}\right) + f_y A_{st}\right] \tag{7}$$

or

$$P_n = 0.85\left[0.85\left\{f_c^{/} + 3.75\left(f_e\right)^{0.79}\right\}\left(A_g - A_{st}\right) + f_y A_{st}\right]$$

(8)

and for tied column:

$$P_n = 0.80\left[0.85\left\{f_c^{/} + 3.75\left(f_e\right)^{0.79}\right\}\left(A_g - A_{st}\right) + f_y A_{st}\right] \tag{9}$$

5. DURABILITY OF CONCRETE BEAMS STRENGTHENED WITH FRP SHEETS/PLATES

The effect of different environmental conditions on reinforced concrete beams strengthened by FRP sheets were investigated by several researchers and still a controversial issue. For instance, the test results by Arntsen and Pedersen [1999] contradict with the general durability effect of moisture condition and freeze-thaw action as noted by other researchers [Chajes and Thomson 1995, Toutanji and Ortiz 1997 and Toutanji et al 1998]. However, the general trend of these environmental exposures is to degrade the flexural or tensile performance of the GFRP composite strengthened specimens and they are more vulnerable to the environmental exposures. It also appears that the behavior of strengthened beams is mostly investigated to explore short-term durability effect and in freezing or room temperature environment like cold or temperate regions of the world. Hence further studies on the durability performance of FRP strengthened beams under long term periods are necessary. Moreover, the long-term durability study in arid region particularly under hot climate has not been conducted yet.

A total of one hundred and two specimens were used for this part of the investigation. The durability performance was determined by evaluating flexural capacity of these specimens after placing them in different environments directly or indirectly with simulated field conditions for a specified period of time.

The specimens were divided into six categories such as laboratory specimens (unexposed category), field specimens (direct exposure to hot-dry field conditions), wet-dry normal water specimens, wet-dry saline (Nacl) water specimens, wet-dry alkaline (NaOH) specimens, high-temperature specimens (50 ^{o}C and 50% relative humidity). Each category consisted of unretrofitted and retrofitted beams. Furthermore, some of the specimens of the field exposure were coated with UV painting. The specimens of different wet-dry environments were exposed to a time cycle of 2 weeks inside the solution and 2 weeks outside the solution. For each category, except the high temperature one, the specimens are scheduled for flexural test at the age of 6, 12 and 24 months of the exposure period. The specimens with high temperature exposure are scheduled for testing after 24 months period. Effects of

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environmental and climatic conditions for unretrofitted and retrofitted specimens are currently an ongoing investigation at the Civil Engineering Department of King Saud University in Riyadh, Saudi Arabia.

At this stage, after an exposure period of six months, only two specimens of each group were tested. The results for the tested beams are presented in Figs. 7 through 9. To facilitate the comparison between the test results for different beams, the same scale is used for all figures. Fig. 7 shows the relationship between the vertical deflection at the beam midspan and the applied load for retrofitted and unretrofitted beams. The results clearly show that there is about 100% gain in the flexural strength of the beams as a result of attaching one layer of GFRP sheet to the tension side of the beam. Fig. 8 clearly reveals that after six months exposure period, there is no sound deterioration on the GFRP sheets due to the direct exposure to solar radiation. Therefore, the load-deflection curves for the specimens exposed to field conditions with or without UV paint are almost the same. However, the degradation effect of the solar radiation is expected to have some negative influence on the strength of the retrofitted beam to be subjected to a prolonged exposure period.

Furthermore, the results reported in Fig. 9 indicate that during the six months testing period none of the wet-dry conditions considered in this study appeared to have played any sensible influence on the flexural strength or flexural rigidity of the beams. However, the wet-dry cycles are continuing for the counterpart specimens and will be tested as per the predefined schedule. It is worth mentioning, previous works (Chajes et al 1995, Toutanji and Ortiz 1997, and Toutanji et al 1998) showed a noticeable ratio of degradation of different types of GFRP materials although the period of exposure, under some environmental conditions similar to those considered in this study, was much less than six months. This may be attributed to the quality of the epoxy used in this study to attach the GFRP sheets to the beams which may have acted as a barrier between the GFRP and the environment. Further studies should, however, be conducted to investigate whether this barrier effect of the epoxy would hold under service load conditions or not.

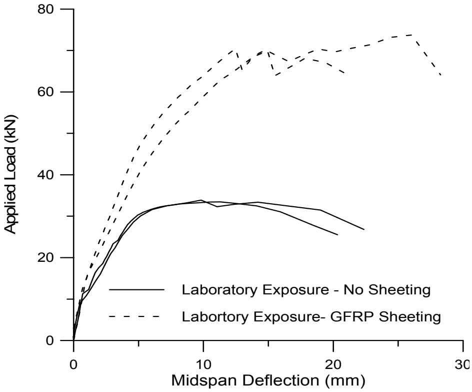

Figure 7: Load-deflection relationship for beams subjected to laboratory conditions.

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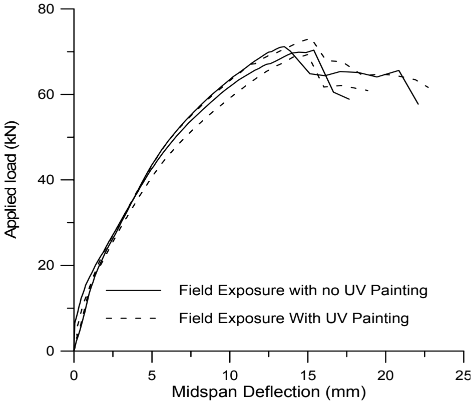

Figure 8: Load-deflection relationship for beams subjected to hot-dry field conditions

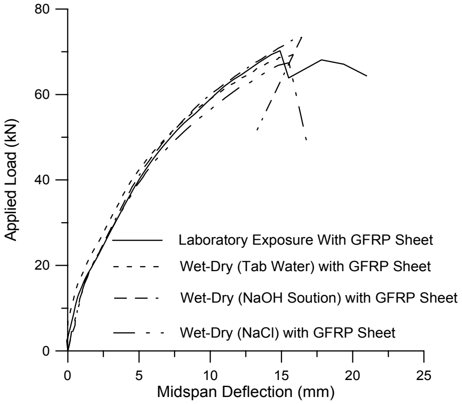

Figure 9: Load-deflection relationship for beams subjected to wet-dry cycles.

6. STRENGTH TEST OF UNREINFORCED MASONRY WALLS RETROFITTED WITH COMPOSITE MATERIAL

Unreinforced masonry (URM) walls are considered as the most vulnerable part of the structures to earthquake forces. Severe damages in URM walls are encountered due to wall movements during earthquakes. In many countries including Kingdom of Saudi Arabia, many of the residential buildings and the infill walls in reinforced concrete structures are of unreinforced masonry structures. It has been identified that the main cause for the loss of lives during an earthquake or blast loading is due to the poor performance of the existing unreinforced masonry structures. The type of failures as commonly observed in the URM walls subjected to seismic force, blast loading or excessive stresses due to partial settlement are the out-of-plane or flexural failure and in-plane or shear failure. Between these two, the flexural or out-of-plane failure has been identified as the most dangerous or critical one for the main cause for the loss of lives. Thus retrofitting or strengthening of the existing masonry wall and repair of the damaged walls have become the prime concern to civil engineering professionals.

In this study, two series of experimental specimens were cast and tested. The major variables considered in the tests include the wall type (red clay bricks or concrete blocks), method of loading, wall dimensions and number of FRP layers. For economic reasons, only GFRP sheets were used with walls. Walls were tested for out of plane stresses, in-plane loading in the vertical direction and in-plane loading in the lateral direction. The test set up is depicted in Figs 10 through 12. The load-deflection curves for four specimens are shown in Fig.13. The results shown in Fig. 13 indicate that by using the FRP sheets, the load carrying capacity of the URM can be increased from 4 to 10 times as that of the original capacity. The limit of the load capacity when using FRP is the compressive strength of the blocks. This is why the wall loaded in the vertical (horizontal block) direction carried less load than the wall loaded in the lateral direction. The increase in the load carrying capacity of the wall when strengthened with FRP sheets may be attributed to the fact that the sheets transferred the wall from one made of individual blocks to a one-unit wall. Furthermore, models that are capable of predicting the load capacity of the strengthened walls whether subjected to flexural or shear stresses are developed. The accuracy of the models are checked by comparing the experimental test results with the corresponding predicted values. Reasonable agreements are obtained between the measured and predicted values.

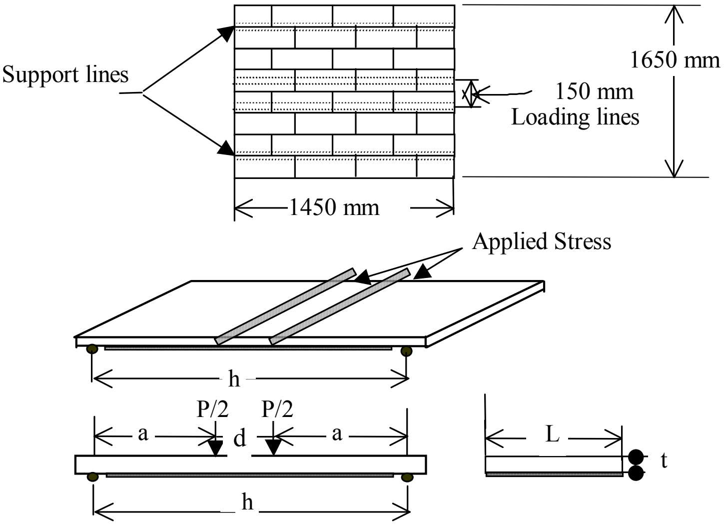

Figure 10: The test setup and dimensions of the out-of-plane block wall specimen.

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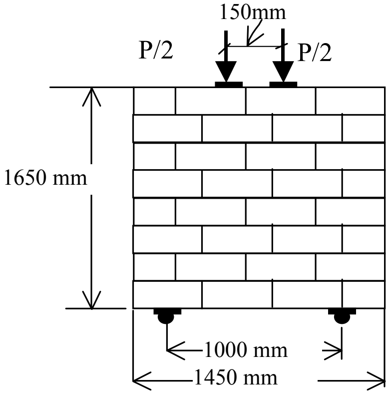

Figure 11: The test setup and dimensions of the in-plane vertically loaded block wall specimen.

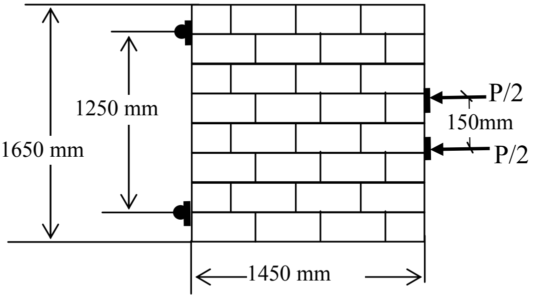

Figure 12: The test setup and dimensions of the in-plane laterally loaded block wall specimen.

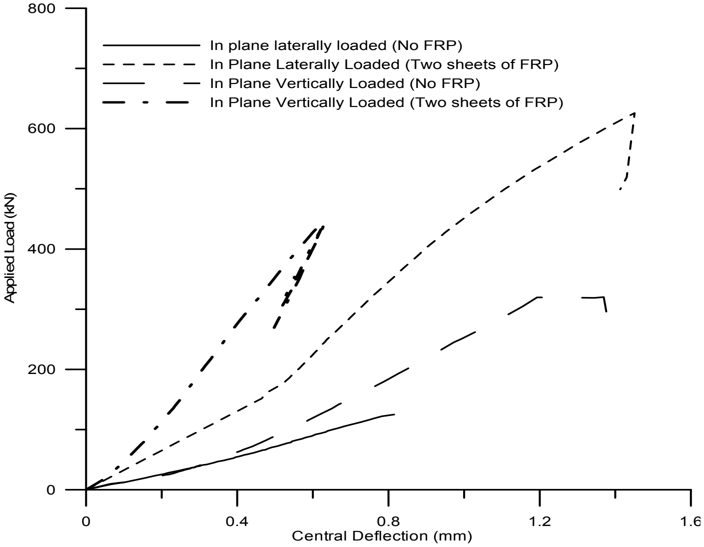

Figure 13: Load-deflection relationship for strengthened and unstrengthened walls subjected to in-plane loadings.

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7. STRENGTH TESTS FOR PIPES RETROFITTED WITH COMPOSITE SHEETS

Whilst pipeline systems have been demonstrated to be a safe and reliable method for the transportation of gas and oil, it is inevitable that over the course of a pipeline's lifetime it will suffer damage that requires repair. Most damage arises from outside forces (external mechanical interference) but defects arising from corrosion, or from construction (welding defects) and material defects (e.g. slivers) can also feature.

There are several repair techniques available for damaged pipelines, the choice of which will be determined by factors such as the extent of the damage, its location, requirement to maintain flow and whether the repair is temporary or permanent. These types would include dressing, close fitting shells, stand-off shells, weld deposition, cut-outs and epoxy-filled shell repairs. However, there is great trend in using FRP to repair/strengthen pipes and there are different techniques to use FRP sheets to repair and/or strengthening of pipes.

In this study, three series of PVC pipes will be tested. The first series will be regarded as control series and the pipes will have no sheets. This series will be pressurized with water until failure. The second series will be identical to the first series except that the specimens will be wrapped with FRP sheets then they will be pressurized until failure The third series will be the same specimens of the second group after being repaired. So far, the first series of tests has been completed. The test specimen is shown in Fig. 14. The results of the tests for the three series will be reported upon completion.

Figure 14. Test specimen for pipes

8. CONCLUSIONS

The idea of using continuous FRP sheets in structural retrofitting/strengthening is relatively new to clients, engineers and consultants in Saudi Arabia. However, the great potential of the materials as has been proven in this study and the amount of data that is now becoming available about the materials are expected to increase the field applications of the materials for different parts of the infrastructure. This is especially true as the repair/strengthening with

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FRP materials are more economical than that of most of other available techniques. There is, however, a need for research cooperation between the local research institution and the material suppliers to account for the influence of local environment and design construction practice on the short and long term behavior of the materials under the prevailing loading and environmental conditions.

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