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Research Paper

Effects of steel corrosion to BFRP Strengthened columns under eccentric loading

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ABSTRACT

The experiment consists of twenty-four mid-scale rectangular RC columns (200x200x800mm) strengthening by BFRP sheets and research variables include: BFRP layer (0, 1, and 3 layers); eccentricity (25mm and 75mm); and 4 levels of steel corrosion. The results reveal that SEL (ratio of ultimate load of strengthened member to that of corresponding controlled member) is direct proportion with steel corrosion while SEV (ratio of ultimate vertical displacement of strengthened member to that of corresponding controlled member) is inverse proportion with steel corrosion; SEL slightly increases with the increase of BFRP layer and eccentricity; but SEV decreases noticeably with the increase of BFRP layer and eccentricity. In addition,the interaction between FRP sheets, stirrups, and longitudinal reinforcement in steel degraded BFRP strengthened columns is very strong.However, column design basing on current design manuals and codes as ACI 440.2R and CNR DT 200R1 has not mentioned this affect. Thus, the load capacity prediction of column being strengthened by BFRP sheets should include levels of steel corrosion for reality, reasonable, and integral of the design.

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1 Introduction

RC columns, one of the load-bearing components in structures, are vulnerable to corrosion problems because they directly contact to environment disadvantage factors, such as moisture, flooding and chloride ions or sulphate dissolved in water… These factors generate corrosion of reinforcement and degrade concrete quality. In Việt Nam, reinforced concrete (RC) structures in saline environment have mostly been under serious deterioration condition after 10 to 30 years of service [1]. Besides traditional methods, strengthening solutions using Fiber Reinforced Polymer (FRP) materials which are

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corrosion resistance, high tension strength, light weight, non-magnetic, and easy for construction and fixing have emerged as efficient methods for RC deficient structures such as piers, columns, piles in saline environment.

Existing studies related to axial compression of FRP wrapping around RC columns immersed in environment can be divided into two groups. The first group carries out experiment concentration on the effectiveness of using Carbon Fiber Reinforced Polymer (CFRP) wrapping around RC column and prestress concrete undergoing corrosion of steel reinforecement with axial compression such as Pantazopoulou et al. [2], Tastani and Pantazopoulou [3], Nossoni and Harichandran [4], Bae and Belarbi [5], Sangeeta et al. [6], Suh et al. [7], Gharachorlou and Ramezanianpour [8], Gadve et al. [9], and G. Nossoni et al. [10]. These researchers have been interested in CFRP sheets in retrofitting load-bearing capacity and preventing environment negative effects. The results reveal that CFRP sheets are highly efficiency in retroffiting RC columns thanks to confinement effect and effective prevention concrete core from oxigen, chloride, sulphate ion and water penetration. However, they have barely analysed concrete corrosion and interaction between stirrups and CFRP sheets. The second group, including researchs by Soudki and Green [11], Toutanji and Balaguru [12], Houssam and Toutanji [13], Gharachorlou and Ramezanianpour [8], El-Hacha et al. [14], Micelli et al.[15], Zhou et al. [16], and Subhani and Al-Ameri [17], studied environment effects on concrete specimens without reinforcement strengthened by FRP sheet wrapping under axial compression. The authors agree that load-bearing capacity decreases while contacting to saline environment. The specimens were first strengthened, then exposing to corrosion environment, and finally testing and evaluating load-bearing capacity and deformation. Although this method can evaluate specimens under saline environment, it cannot achieve the phenomena of actual structures which are corroded before strengthening. In addition, because of specimens without reinforcement, these studies cannot analyze the influence of reinforcement corrosion which happening when specimens expose long time in saline environment.

In general, most of the studies have been carried out on specimens strengthened CFRP under axial compression and there is no study performing corrosion columns strengthened by Basalt Fiber Reinforced Polymer (BFRP) under eccentric loading. In addition, most of existing studies concentrated on surveying and analysing load-bearing capacity and interaction between FRP and longitudinal reinforcement but it is rarely mentioned stirrup corrosion (although stirrups' corrosion happens before longitudinal reinforcements' corrosion). In reality, spiral stirrup or enough stirrup content, stirrup confinement substantially contributes to specimen load-bearing capacity. The interaction between corrosion stirrup and FRP sheets and its affects to column load-bearing capacity need to be made clear for adequacy and safety design.

2 Testing program

2.1 Material

A total of twenty-four short columns were tested for comprehensive parametric study. Figure 1 presents the specimen detail of columns. Four rebars with a diameter of 16mm and the nominal yield strength of 350MPa were used as longitudinal reinforcement. Steel rebars with a diameter of 6mm were used for stirrups. The concrete strengths were 46MPa for all specimens. BFRP sheets with tensile strength and the elastic modulus of 2131 MPa and 105 GPa were used to strengthen RC columns by using epoxy-based resins.

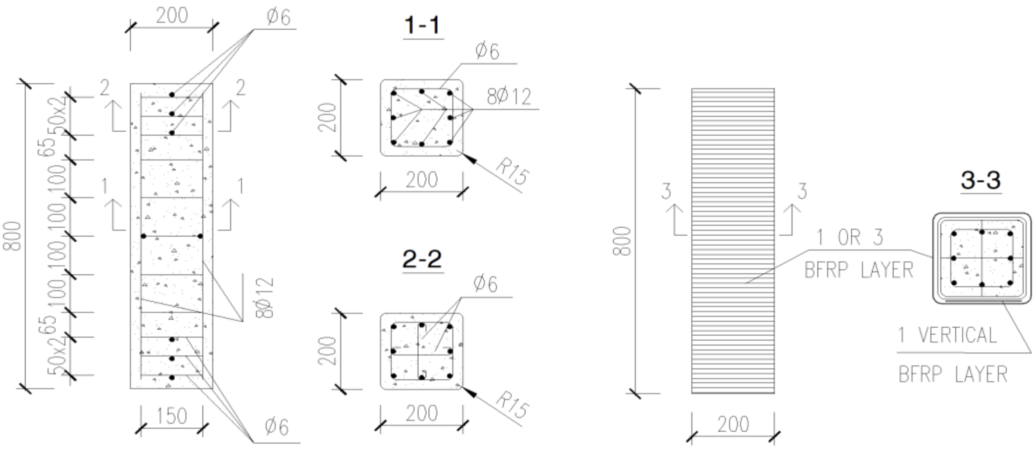


Fig. 1 – Specimen detail.

2.2 Specimens and Testing

The twenty-four columns were tested and summarized in Table 1, and variables includes: BFRP layer (1 and 3 layers); eccentricity (25 and 75 mm); and steel corrosion (4 levels: group A with no corrosion, group B with stirrup corrosion of 15% weight, group C with both stirrup and longitudinal reinforcement corrosion of 15%, and group D with stirrup corrosion of 15% and longitudinal reinforcement corrosion of 30%). Before casting, steel reinforcement was corroded by H_2SO_4 solution of 40% and daily checked corrosion level by comparing weights of sample bars after removing rust with original ones. Tested columns were measured by thirteen strain gauges (SGs), including two SGs for stirrups, four SGs for longitudinal reinforcement, three SGs for concrete and four SGs for BFRP sheet. Axial and lateral displacement were measured by six linear variable differential transformers (LVDTs). Loading steps of 10-20kN/min are used and all the data is automatically collected.

Table 1 – Specimens and Results.

Speci_ men	**BFRP Layers**	**Eccen_ tricity (mm)**	**P_u (KN)**	**δ_{vu} (mm)**	**Speci_ men**	**BFRP Layers**	**Eccen_ tricity (mm)**	**P_u (KN)**	**δ_{vu} (mm)**
A00-25	0	25	1315	3.3	C00-25	0	25	1255	4.0
A00-75	0	75	695	4.6	C00-75	0	75	576	6.4
A11B25	1	25	1525	4.6	C11B25	1	25	1406	4.3
A13B25	3	25	1586	3.8	C13B25	3	25	1542	5.2
A11B75	1	75	810	5.4	C11B75	1	75	720	6.7
A13B75	3	75	810	4.7	C13B75	3	75	794	7.0
B00-25	0	25	1221	3.5	D00-25	0	25	1071	5.0
B00-75	0	75	676	5.4	D00-75	0	75	477	8.0
B11B25	1	25	1489	4.6	D11B25	1	25	1393	4.5
B13B25	3	25	1578	3.9	D13B25	3	25	1528	4.6
B11B75	1	75	759	6.1	D11B75	1	75	673	8.7
B13B75	3	75	800	5.3	D13B75	3	75	741	7.2

3 Results and analysis

3.1 Failure modes

For controlled specimens, failure happens in the middle due to concrete breaking (Figure 2). Cracks is formed in the middle at load of 45-50%P_u (P_u is failure load), being recorded through splitting sounds lasting to failure. Concrete core at specimen's middle is intact and strains of longitudinal reinforcement and stirrups are small.

BFRP local peel-off phenomena happens with BFRP strengthened specimens under wet-dry cycles at load of 45-50%P_u (Figure 2). These phenomena are recorded through vision and splitting sounds of resin failure. At early state, local peel-off BFRP is scattered on the specimens, and at final stage, peel-off BFRP is concentrated at failure area. At ultimate load, BFRP sheets are suddenly torn with a sound; the higher concrete strength and higher number of BFRP strengthened layers are, the bigger sound is.

Fig. 2 – Failure of controlled and BFRP strengthened specimens.

3.2 Load-bearing capacity

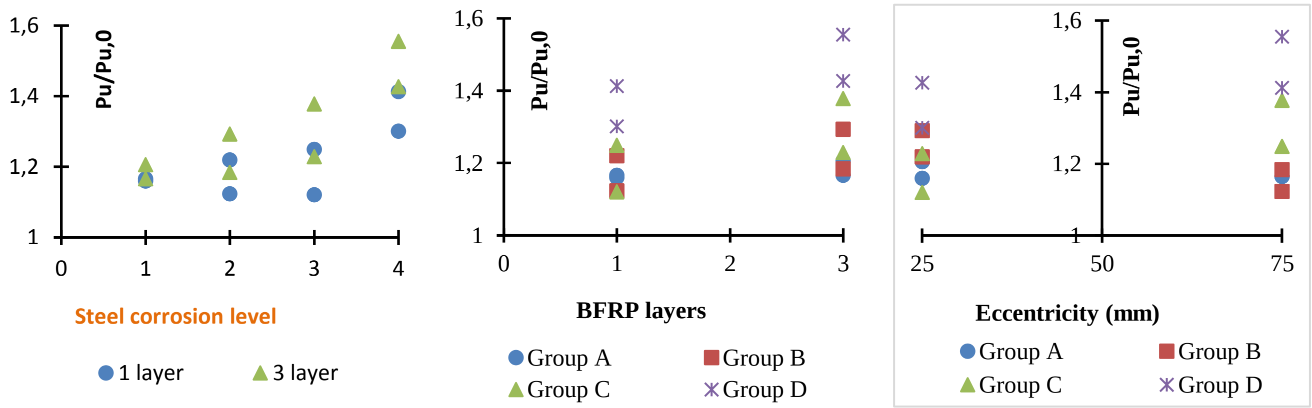


Fig. 3 – Load-bearing capacity comparing with controlled specimens.

Strengthened-Effectiveness of Load-bearing capacity (SEL) is defined as ratio of ultimate load of strengthened member (P_u) to that of corresponding controlled member ($P_{u,0}$). According to Figure 3, SEL is direct proportion with steel corrosion while and SEL slightly increases with the increase of BFRP layer and eccentricity. When increasing level of steel corrosion from A to D, SEL increases from 1.12 to 1.41 for 1-layer BFRP specimens and from 1.17 to 1.55 for 3-layer BFRP specimens. The explanation is that specimens load-bearing capacity reduce while BFRP strengthening is constant for corresponding ones. SEL also increases with the increase of BFRP layer and eccentricity; but these increases are small.

3.3 Vertical displacement

Strengthened-Effectiveness of Vertical displacement (SEV) is defined as ratio of ultimate vertical displacement of strengthened member (δ_{vu}) to that of corresponding controlled member ($\delta_{vu,0}$). As Figure 4, SEV is inverse proportion with steel corrosion and SEV decreases noticeably with the increase of BFRP layer and eccentricity. When increasing level of steel corrosion from A to D, SEV decrease sharply from 1.37 to 0.90. This happens due to the vertical displacement increasing of controlled members are relatively large compared with corresponding strengthened member. SEV also decreases with the increase of BFRP layer and eccentricity.

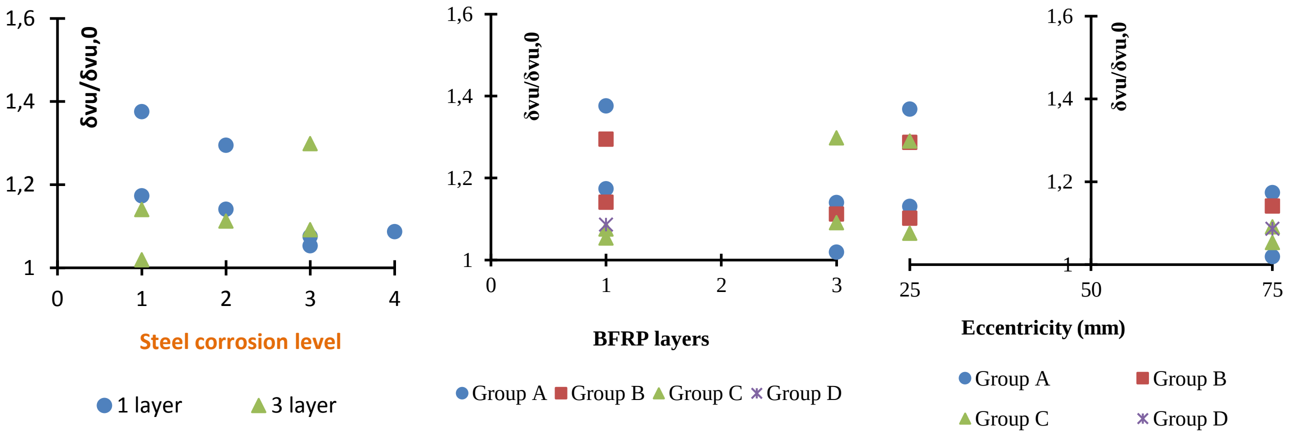


Fig. 4 – Vertical displacement comparing with controlled specimens.

3.4 Interaction between stirrups, BFRP, and longitudinal reinforcement

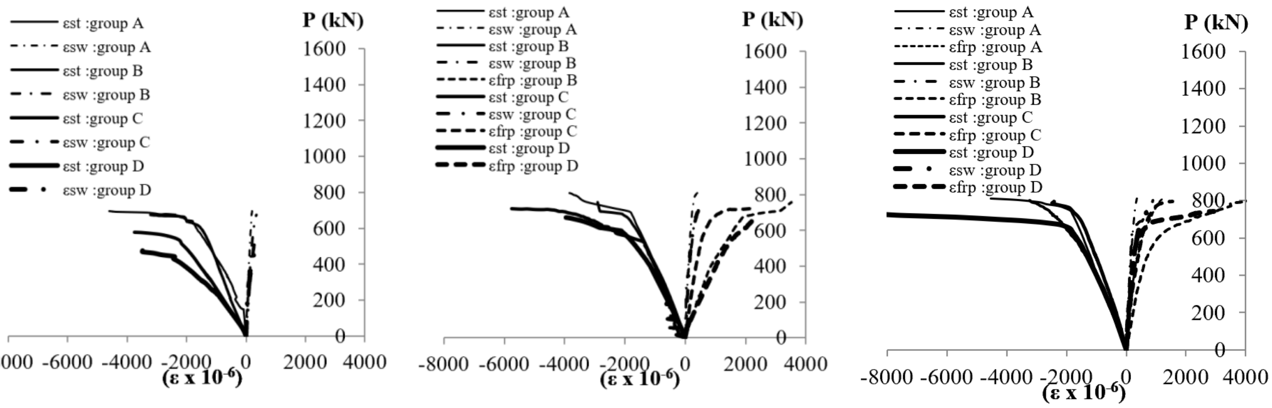
Stirrups confine the concrete core of specimens and longitudinal reinforcement is directly bearing axial loads. Figure 5 shows that corrosion of steel reduces concrete stiffness and increases stirrup and longitudinal reinforcement strains. At the same load level, the higher levels of corrosion are, the higher these strains are. However, at ultimate load level, the steel corrosion effect on the ultimate strains is not substantial. The increase of these ultimate strains tends to increase with the increase of BFRP strengthened layers and decrease with the increase of eccentricity.

According to Maguire et al. [18], correlated coefficient of 2 variables x and y (r_{xy}) calculated as:

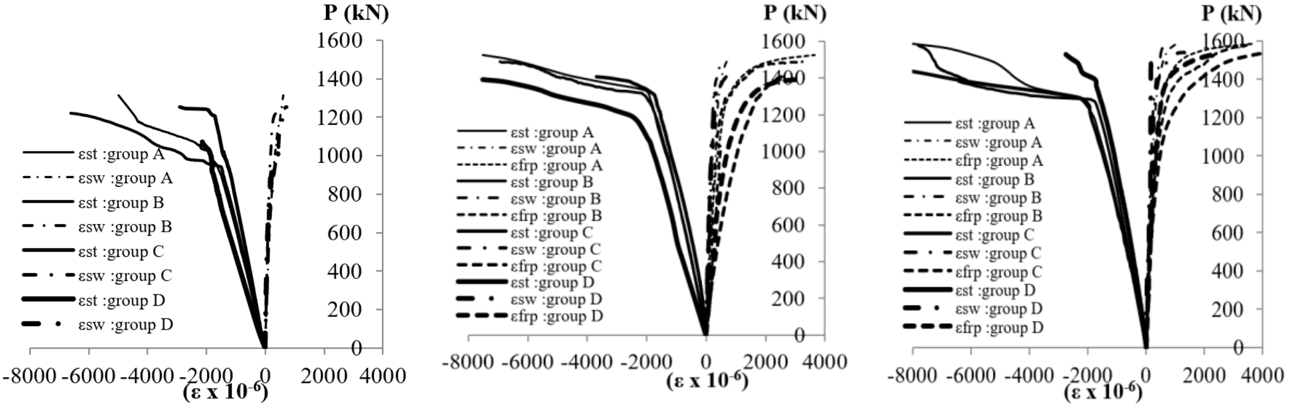
$$r_{xy} = \frac{\sum_{i=1}^{ns}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{ns}(x_i - \overline{x})^2}\sqrt{\sum_{i=1}^{ns}(y_i - \overline{y})^2}} \tag{1}$$

In this formula, x is stirrup strain of unstrengthened specimens ($\varepsilon_{sw.o}$); y is strain of BFRP strengthened specimens ($\varepsilon_{sw.u}$); x¯is mean of ns values of x; y¯is mean of ns values of y. If r_{xy} value is approximate 1, the correlation of x and y is strongly linear. Otherwise, if r_{xy} value is less than 0.2, the correlation of x and y is weakly linear.

According to Figure 6, interaction between stirrups and number of BFRP strengthened layers is strongly linear with r_{xy} value of 0.86 and 0.99. BFRP sheets have a great contribution in promoting stirrups' working ability and strain. Current manuals for determining load-bearing ability of columns like ACI 440.2R [19] or CNR DT200 [20] mention stirrups' contribution as a factor without reflecting the interaction between stirrups and BFRP sheets.



a) Controlled specimen; e=25mm b) 1 BFRP layer; e=25mm c) 3 BFRP layers; e=25mm



d) Controlled specimen; e=75mm e) 1 BFRP layer; e=75mm f) 3 BFRP layers; e=75mm

Fig. 5– Load – relative strains of BFRP, stirrup, and longitudinal reinforcement relationship

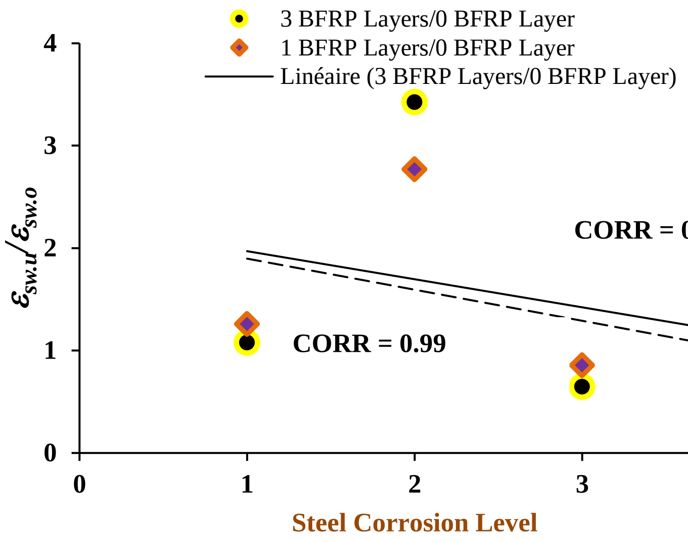


Fig. 6 – The interaction between stirrup and BFRP

4 Conclusion

This study investigates the effect of steel corrosion on the strengthening efficiency of BFRP sheet wrapping for short reinforced concrete (RC) columns subjected to eccentric compressive loading. Main investigated variables include BFRP layer, eccentricity, and steel corrosion; and the findings in this study can be summarized as follows: Load-bearing capacity and vertical displacement increase with the increase of BFRP layers. However, SEL is direct proportion with steel corrosion while SEV is inverse proportion with steel corrosion; SEL slightly increases with the increase of BFRP layer and eccentricity; but SEV decreases noticeably with the increase of BFRP layer and eccentricity; For all investigated steel corrosion, stirrups' and longitudinal reinforcements strains increase significant with BFRP strengthened specimens and the higher the BFRP layers are, the larger the steel strains are; The formulas for estimation of axial-compression capacity of the columns strengthened by FRP sheet wrapping provided in the current design recommendations and codes such as ACI 440.2R [19] and CNR DT 200R1[20] have not considered the interaction between FRP sheets, stirrups, and longitudinal reinforcement. This interaction should be considered into the formulas for the estimation to be more accurately and physically.

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REFERENCES

[1]- C.D. Tien, Final Report for Technology and Economical Project of Corrosion Protection of Marine Structure, Vietnam Inst. for Build. Science and Technology (in Vietnamese), 11/2003.

[2]- S.J. Pantazopoulou, J.F. Bonacci, S. Sheikh, M.D.A. Thomas, N. Hearn, Repair of corrosion-damaged columns with FRP wraps. J. Comp. Cons. 5(1) (2001) 3–11. doi:10.1061/(ASCE)1090-0268(2001)5:1(3)

[3]- S.P. Tastani, S.J. Pantazopoulou, Experimental evaluation of FRP jackets in upgrading RC corroded columns with substandard detailing. Eng. Struct. 26(6) (2004) 817-829. doi:10.1016/j.engstruct.2004.02.003

[4]- G. Nossoni, R.S. Harichandran, Improved durability of patched concrete bridges against corrosion by using an FRP overlay. In: Proceedings of 86th Annual Meeting of the Transportation Research Board, Transportation Research Board, Washington, DC, 2014.

[5]- S.W. Bae, A. Belarbi, Effects of corrosion of steel reinforcement on RC columns wrapped with FRP sheets. J. Perform. Constr. Facil. 23(1) (2009) 20–31. doi:10.1061/(ASCE)0887-3828(2009)23:1(20)

[6]- S. Gadve, A. Mukherjee, S. N. Malhotra, Corrosion of steel reinforcements embedded in FRP wrapped concrete.

Cons. Build. Mater. 23(1) (2009) 153–161. doi:10.1016/j.conbuildmat.2008.01.008

[7]- K. Suh, G. Mullins, R. Sen, D. Winters, Effective repair for corrosion control using FRP wraps. J. Comp. Cons., 14 (2010) 388–396. doi:10.1061/(ASCE)CC.1943-5614.0000094

[8]- A. Gharachorlou, A.A. Ramezanianpour, durability of concrete cylinder specimens strengthened with frp laminates under penetration of chloride ions. Int. J. Civ. Eng. 8 (4) (2010) 327 – 336.

[9]- S. Gadve, A. Mukherjee, S.N. Malhotra, Active protection of fiber-reinforced polymer-wrapped reinforced concrete structures against corrosion. Corros. 67(2) (2011) 1–11. doi:10.5006/1.3549564

[10]- G. Nossoni, R.S. Harichandran, M.I. Baiyasi, rate of reinforcement corrosion and stress concentration in concrete columns repaired with bonded and unbonded FRP wraps. J. Comp. Cons. 19 (5) (2015). doi:10.1061/(ASCE)CC.1943-5614.0000547

[11]- K.A. Soudki, M.F. Green, Freeze-Thaw Response of CFRP Wrapped Concrete. Concr. Int. 19(8) (1997) 64-67.

[12]- H. Toutanji, P. Balaguru, Durability characteristics of concrete columns wrapped with FRP tow sheets. J. Mater. Civ. Eng. 10(1) (1998) 52 – 57.

[13]- H. Toutanji, stress-strain characteristics of concrete columns externally confined with advanced fiber composite sheets. J. Mater. 93(3) (1999) 397-404.

[14]- R. El-Hacha, M.F. Green, G.R. Wight, Effect of Severe Environmental Exposures on CFRP Wrapped Concrete Columns. J. Compos. Constr. 14(1) (2010) 83 – 93. doi:10.1061/(ASCE)CC.1943-5614.0000074

[15]- F. Micelli, R. Mazzotta, M. Loene, M.A. Aiello, Review study on the durability of FRP-confined concrete. J Compos. Constr. 19(3) (2015) 04014056. doi:10.1061/(ASCE)CC.1943-5614.0000520

[16]- Y. Zhou, Z. Fan, J. Du, L. Sui, F. Xing, Bond behavior of FRP-to-concrete interface under sulfate attack: An experimental study and modeling of bond degradation, Constr. Build. Mater. 85 (2015) 9–21. doi:10.1016/j.conbuildmat.2015.03.031

[17]- M. Subhani, R. Al-Ameri, Strength reduction in square columns confined with CFRP under marine environment. Compos. Part B: Eng. 97 (2016) 183–192. doi:10.1016/j.compositesb.2016.05.016

[18]- M. Maguire, M. Chang, W.N. Collins, Y. Sun, Stress increase of unbonded tendons in continuous posttensioned members. J. Bridge Eng. 22(2) (2017) 225-241. doi:10.1061/(ASCE)BE.1943-5592.0000991

[19]- ACI 440.2R-17 (2017), Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, Farmington Hills, ACI, USA.

[20]- CNR-DT200 R1 (2013), Guide for the design and construction of externally bonded FRP systems for strengthening of existing structures, CNR Advisory Committee, Rome, Italy.