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Cost and Ductility Effectiveness of Concrete Columns Wrapped with CFRP and SFRP Sheets

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ABSTRACT: Repair and rehabilitation of reinforced concrete (RC) columns using Fibre Reinforced Polymers (FRP) proved to be a very effective technique to enhance the strength and ductility. Recently, a new type of materials called Steel FRP (SFRP) sheets has been introduced for the repair and rehabilitation of concrete structures. Few researches have been performed on the behaviour of the concrete columns wrapped with SFRP sheets; however, several critical parameters such as the cost and ductility effectiveness of the SFRP wrapped columns have been lightly addressed. Thus, the main objective of this paper is to study the cost and ductility effectiveness of SFRP wrapped concrete columns and comparing the results with the conventionally used Carbon FRP (CFRP) wrapped concrete columns. The experimental program consists of eighteen large-scale columns (300×1200mm) divided into five groups (A, B, C, D, and E). The groups varied according to the column type (unwrapped, CFRP wrapped columns and SFRP wrapped columns), column reinforcement ratio (non-reinforced and reinforced), environmental exposure conditions (room temperature of +22°C and freeze-thaw cycling of +34°C to −34°C) and FRP wrapping orientation (circumferential: 0° and longitudinal/circumferential: 90°/0°). The cost effectiveness is determine through an efficiency parameter, which is determined as the ratio of the confined concrete compressive strength of the FRP wrapped specimens normalized with respect to the unwrapped specimens, over the total normalized cost of the FRP confined concrete column. However, the ductility efficiency is determined based on the ratio of the FRP wrapped columns ductility normalized with respect to the unwrapped columns, over the total normalized cost of the FRP confined concrete column. Accordingly, the cost and ductility effectiveness study indicated that the SFRP wrapped RC columns showed better enhanced performance over the CFRP wrapped RC columns.

1 INTRODUCTION

Strengthening of reinforced concrete (RC) columns using Fibre Reinforced Polymers (FRP) is one of the very efficient methods to enhance the strength and ductility of the concrete. The FRP types commonly used for confinement applications are Carbon FRP (CFRP), Glass FRP (GFRP), Aramid FRP (AFRP), and Steel FRP (SFRP). There is an ample amount of information available in the literature concerning the behaviour of RC columns wrapped with CFRP, GFRP and AFRP sheet (few are listed: Karbhari and Eckel, 1994; Nanni and Bradford, 1995; Karbhari and Goa, 1997; Mirmiran and Shahawy, 1997; Tuoutanji, 1999; and Toutanji and Deng, 1999; Karbhari et al., 2000; Karbhari, 2000; Pessiki et al., 2001; Lam and Teng, 2004; Masia et al., 2004; Thériault et al., 2004; Matthys et al., 2006; El-Hacha et al., 2010). However, only recently, SFRP sheets have been attracted by researchers for confinement applications due to the significant enhancement it offers to the RC columns, compared to the conventional FRP sheets

(Thermou and Pantazopoulou, 2007; El-Hacha and Mashrik, 2012; El-Hacha and Abdelrahman, 2013).

Based on experimental data and research, the behaviour of SFRP wrapped concrete columns subjected to normal room temperature, freeze-thaw, humidity and prolonged high temperature was superior to columns wrapped with the conventionally used CFRP sheets (Mashrik, 2011; Abdelrahman, 2011; Abdelrahman and El-Hacha, 2012). Yet, the cost and ductility effectiveness parameters are other criteria required to evaluate the effectiveness of the SFRP sheets for confinement applications. Thus, in this paper, the cost and ductility effectiveness parameters of SFRP and CFRP wrapped concrete columns are evaluated and compared.

Table 1. Summary of the experimental program

Group	FRP Type	FRP Orientation	Exposure	Column ID
A	Unwrapped	-	22^{o}C	NR-CT-RT
	CFRP	0^o	22^{o}C	NR-CFRP-RT
	SFRP	0^o	22^{o}C	NR-SFRP-RT
B	Unwrapped	-	–34^{o}C to +34^{o}C	NR-CT-EE
	CFRP	0^o	–34^{o}C to +34^{o}C	NR-CFRP-EE
	SFRP	0^o	–34^{o}C to +34^{o}C	NR-SFRP-EE
C	Unwrapped	-	22^{o}C	R-CT-RT
	CFRP	0^o	22^{o}C	R-CFRP-RT
	CFRP	90^o/0^o	22^{o}C	R-CFRP-HV-RT
	SFRP	0^o	22^{o}C	R-SFRP-RT
	SFRP	90^o/0^o	22^{o}C	R-SFRP-HV-RT
D	Unwrapped	-	–34^{o}C to +34^{o}C	R-CT-EE
	CFRP	0^o	–34^{o}C to +34^{o}C	R-CFRP-EE
	CFRP	90^o/0^o	–34^{o}C to +34^{o}C	R-CFRP-HV-EE
	SFRP	0^o	–34^{o}C to +34^{o}C	R-SFRP-EE
	SFRP	90^o/0^o	–34^{o}C to +34^{o}C	R-SFRP-HV-EE
E	CFRP	0^o	–34^{o}C to +34^{o}C	R-CFRP-AEE
	SFRP	0^o	–34^{o}C to +34^{o}C	R-SFRP-AEE

2 EXPERIMENTAL PROGRAM

The experimental program consists of 18 large-scale columns with dimensions of 300 mm in diameter and 1200 mm in height. The columns were divided into five groups (A, B, C, D, and E), which varied according to the column type (unwrapped, CFRP wrapped columns and SFRP wrapped columns), column longitudinal reinforcement ratio (non-reinforced and reinforced), environmental exposure conditions (room temperature of +22^{o}C and freeze-thaw cycling of +34^{o}C to –34^{o}C) and FRP wrapping orientation (circumferential: 0^o and / longitudinal/circumferential: 90^o/0^o). The addition of an inner longitudinal FRP layer is to investigate the durability performance of the concrete, in an attempt to enhance the durability performance of the concrete. Also, the inner longitudinal FRP layer was intended to regulate the crack distribution and reduce the stress concentration on the outer circumferential FRP layer to increase the strain efficiency of the FRP sheet. A summary of the experimental program is provided in Table 1.

The specimen ID shown in Table 1 can be described as follows: the first letter designates the research group ("NR" refers to non-reinforced and "R" refers to reinforced columns), followed by the letters representing the wrapping material ("CT" for control unwrapped specimens, "CFRP" for CFRP wrapped sheets, and "SFRP for SFRP wrapped sheets). In some cases, the third letter indicates the wrapping orientation (0^o for the circumferential direction and 90^o for the longitudinal direction) where "HV" refers to columns strengthened horizontally and vertically, and the last letter refers to the type exposure ("RT" for room temperature, "EE" for environmental exposure conditions before FRP wrapping and "AEE" for the columns wrapped after environmental exposure).

It is important to note that the columns were wrapped such that the axial stiffness of the SFRP and the CFRP confined concrete columns are equivalent (EA_{CFRP}= 24.92 MN and EA_{SFRP}= 25.05MN, where E is the modulus of elasticity of the FRP sheets and A is the area/one meter of width) for comparison purposes. Wrapping the columns with one layer of the CFRP sheet has almost an equivalent axial stiffness to the columns wrapped with one layer of the SFRP sheets. The experimental program was designed to study the effect of the steel reinforcement, environmental exposure, and the wrapping orientation of the FRP sheet. Further information about the material and geometric properties of this study can be found in Abdelrahman (2011).

3 COST EFFECTIVENESS

One of the methods to evaluate the effectiveness of the FRP sheet is to consider the cost effectiveness parameter. The cost effectiveness parameter is a function of the strength gain relative to the total cost associated with the construction and the FRP wrapping of the concrete column. Incorporating the cost parameter in the evaluation process is an important criterion for the acceptance of the SFRP sheet as an effective material for concrete enhancement. Thus, the cost effectiveness of the CFRP and the SFRP sheets are presented and compared.

The cost effectiveness parameter is defined through a strength efficiency scale, SE_{ff}, which is determined as the ratio of the confined concrete compressive strength of the FRP wrapped specimens normalized with respect to the unwrapped specimens, over the total cost involved with the construction and the FRP confinement of the concrete column as described in the following equation:

$$SE_{ff} = \frac{Normalized\ FRP\ Confined\ Concrete\ Strength}{Total\ Normalized\ Cost\ of\ the\ FRP\ Confined\ Concrete\ Column} \times 100 \quad (1)$$

As the cost of the concrete, reinforcing steel, epoxy, and transportation are equivalent for all the columns, it is reasonable to ignore these costs for the calculation of the cost effectiveness parameter using Equation 1. The labour costs involved for SFRP wrapped concrete columns are predicted to be higher than the CFRP wrapped concrete columns due to the time and effort required to handle and wrap the stiff SFRP sheets. Based on the laboratory experience gained during the implementation of this project, it was noted that the time required to wrap a column with the SFRP sheet is approximately double the time required to confine the column with the CFRP sheet. This was due to the facts that the SFRP sheet is not as flexible as the CFRP sheet and the requirement of using sonotubes around the wrapped stiff SFRP sheets will prevent it from opening and detaching from the concrete surface. Clamps were also used to tighten the sonotubes in order to ensure that the SFRP sheets are in complete contact with the circumferential concrete surface, such requirement was not necessary when flexible CFRP sheets were wrapped around the concrete column. Thus, the labour cost for the SFRP wrapped concrete column is estimated to be twice the labour cost involved for CFRP wrapped concrete column.

Based on the 2011 market price (at the time this research was conducted), the cost of the SFRP and CFRP sheets are 25 $\$/m^2$ and 45 $\$/m^2$, respectively (Abdelrahman 2011). Therefore, the cost of the SFRP sheet is 56 % of the CFRP sheet cost. The labour cost is a varying factor, thus, in order to avoid this, the labour cost has been normalized to yield a factor of 1 and 2 for the CFRP and the SFRP wrapped concrete columns, respectively. The normalized factors are based on the abovementioned estimates that the labour cost of the SFRP wrapped concrete column is twice that of the CFRP wrapped concrete column. In addition, the material cost of the FRP sheets has been normalized with respect to the material cost of the CFRP sheet. Thus, the normalized material cost for the SFRP and the CFRP sheets is 0.55 and 1.0, respectively. Accordingly, the total normalized cost for the SFRP and the CFRP wrapped columns is 2.0 and 2.55, respectively.

The normalized strength and the cost effectiveness of the SFRP and the CFRP wrapped concrete columns are presented in Figure 1 and Figure 2, respectively. The CFRP wrapped non-reinforced concrete (NRC) columns (NR-CFRP-RT and NR-CFRP-EE) had higher cost effectiveness than the CFRP wrapped RC columns (R-CFRP-RT, R-CFRP-EE, R-CFRP-HV-RT, R-CFRP-HV-EE and R-CFRP-AEE). This is due to the fact that the confined concrete strength increase of the CFRP wrapped NRC columns was higher than the CFRP wrapped RC columns. In addition, there is an insignificant change (less than 10% difference) in the cost effectiveness of the columns wrapped with one layer of CFRP sheet in the longitudinal direction (R-CFRP-RT and R-CFRP-EE) and the columns strengthened with two layers of CFRP sheet one in the longitudinal direction and one wrap in the transverse direction (R-CFRP-HV-RT and R-CFRP-HV-EE). This result is expected since the longitudinal layer of the CFRP sheet does not contribute to the axial stiffness of the columns and as a consequence, no strength gain is recognized due to the addition of this layer. The results also show that wrapping the columns with CFRP sheet after environmental exposure (R-CFRP-AEE) had an insignificant effect on the cost effectiveness compared to the columns wrapped with the CFRP sheet before environmental exposure (R-CFRP-EE and R-CFRP-HV-EE). This is due to the fact that during environmental exposure, the FRP sheet acted as a protective layer to the concrete, and no deterioration of the FRP sheet occurred because of the non-corrosive properties of the FRP sheet. Thus, the behaviour of the columns wrapped before environmental exposure was very similar to the columns wrapped after environmental exposure.

During the experimental testing, it was noted that the SFRP wrapped NRC column subjected to environmental exposure (NR-SFRP-EE) experienced premature failure as an accidental eccentricity was applied from the loading plates of the testing machine. If this column was to be ignored, the results clearly show that all the concrete columns confined with the SFRP sheets achieved similar cost effectiveness with a maximum percentage difference of 11 %. This small percentage difference is strongly believed to be attributed to the nature of the strength variability of the concrete. Based on Figure 2, the results show that the CFRP wrapped NRC columns (NR-CFRP-RT and NR-CFRP-EE) had higher cost effectiveness that the SFRP wrapped NRC columns (NR-SFRP-RT and NR-SFRP-EE). However, Figure 2 also indicates that for RC columns, regardless of the internal longitudinal reinforcement ratio, the type of environmental exposure, and the FRP wrapping orientations of the columns, the cost effectiveness of the columns wrapped with the SFRP sheets is always superior to the columns wrapped with the CFRP sheets.

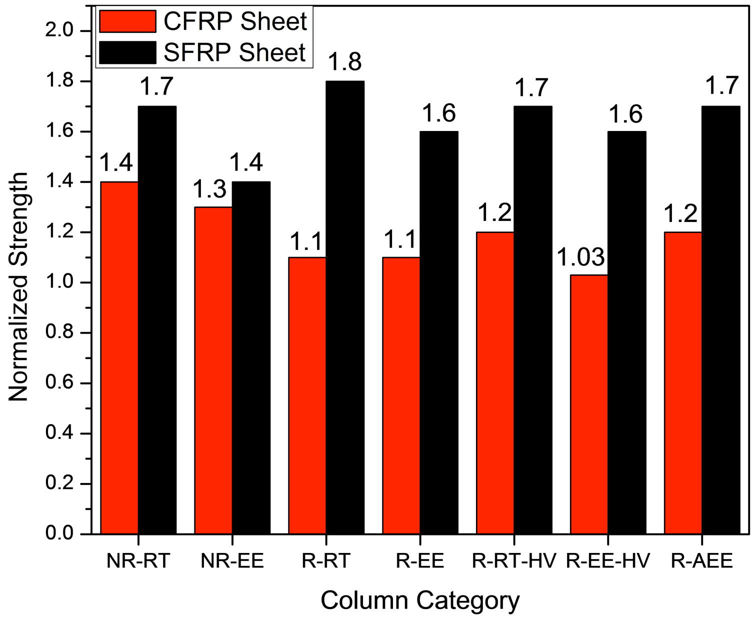

Figure 1. Percentage increase in the strength of the SFRP and the CFRP wrapped concrete columns. [The test specimens include non-reinforced and reinforced concrete columns]

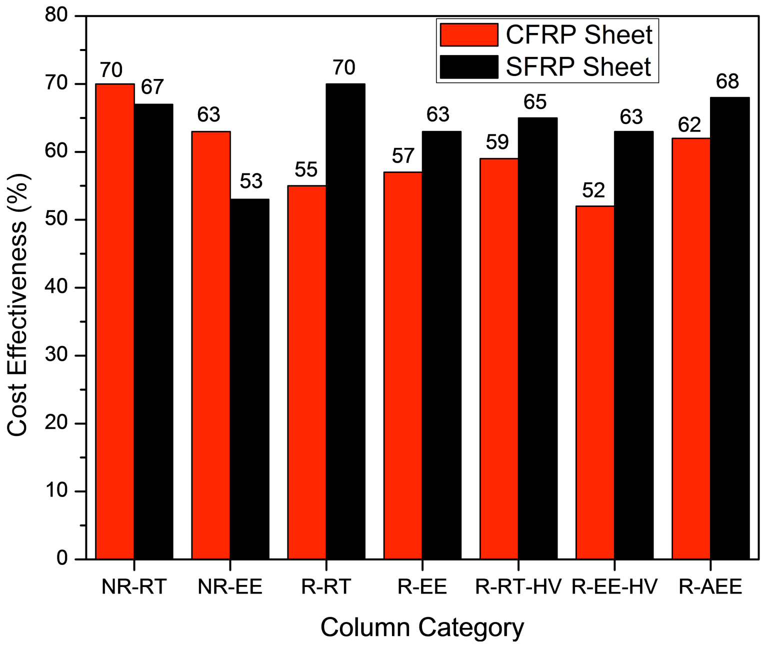

Figure 2. Cost effectiveness of the CFRP and the SFRP wrapped concrete columns.

4 DUCTILITY EFFECTIVENESS

Another method to evaluate the effectiveness of the various types of FRP sheets to confine RC columns is to consider the ductility effectiveness parameter. Similar to the cost effectiveness parameter, the ductility effectiveness parameter is a function of the ductility gain relative to the total cost associated with the construction and the FRP confinement of the concrete column. The ductility of the columns was measured as the total area under the stress-strain curve up to the failure load of the experimentally tested SFRP/ CFRP wrapped concrete columns. The failure load is defined as the load corresponding to the rupture of the confining FRP sheet. The ductility of the FRP wrapped concrete columns normalized with respect to its corresponding unwrapped control specimen is shown in Figure 3. The strain efficiency, defined as the maximum strain at rupture of the FRP confined concrete columns to the ultimate tensile strain of the FRP sheets is reported by Abdelrahman (2011). The ductility effectiveness parameter is very important when considering strengthening the columns subjected to seismic or eccentric loading. Thus, in this section, the ductility effectiveness of the columns confined with SFRP and CFRP sheets are evaluated and compared.

The ductility effectiveness is defined through a ductility efficiency scale, DE_{ff}, which is determined as the ratio of the ductility of the FRP wrapped columns normalized with respect to the unwrapped columns, over the total cost associated with the construction and the FRP confinement of the concrete column as described in the following equation:

$$DE_{ff} = \frac{Normalized\ Ductility\ of\ the\ FRP\ Confined\ Concrete\ Column}{Total\ Normalized\ Cost\ of\ the\ FRP\ Confined\ Concrete\ Column} \times 100 \qquad (2)$$

The cost of the SFRP/CFRP and the labour costs are considered due to the reasons already mentioned above.

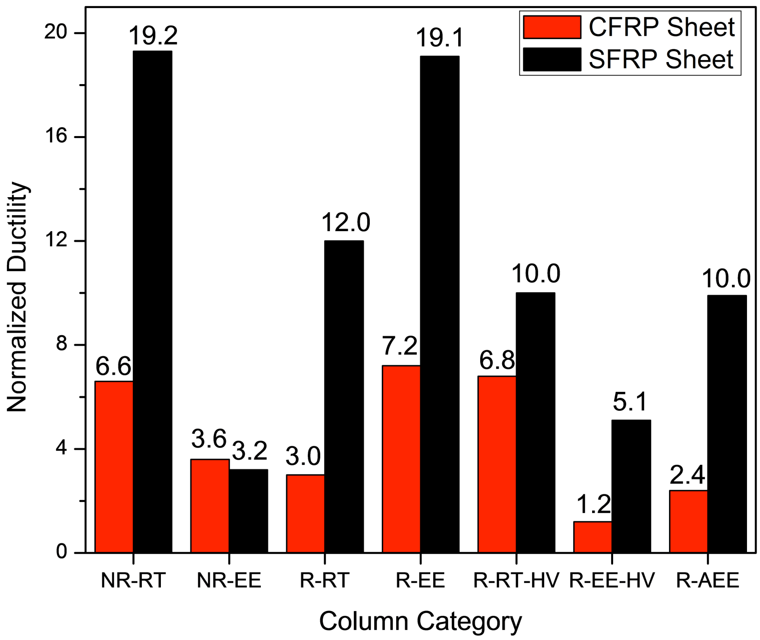

Figure 3. Percentage increase in the ductility of the SFRP and the CFRP wrapped columns.

In the comparison of the ductility effectiveness parameter, only the cost of labour and the cost of the CFRP and SFRP sheets are considered due to the reasons already mentioned above. The data presented in Figure 4 shows that there is no general trend that can be recognized within the groups of CFRP and SFRP wrapped concrete columns. However, if the SFRP wrapped NRC column (NR-SFRP-EE) is excluded from the analysis due to reasons explained earlier, it can be stated that regardless of the internal longitudinal reinforcement ratio, the type of environmental exposure, and the FRP wrapping orientations of the columns, the ductility effectiveness of the columns wrapped with the SFRP sheets is always superior to the columns wrapped with the CFRP sheets.

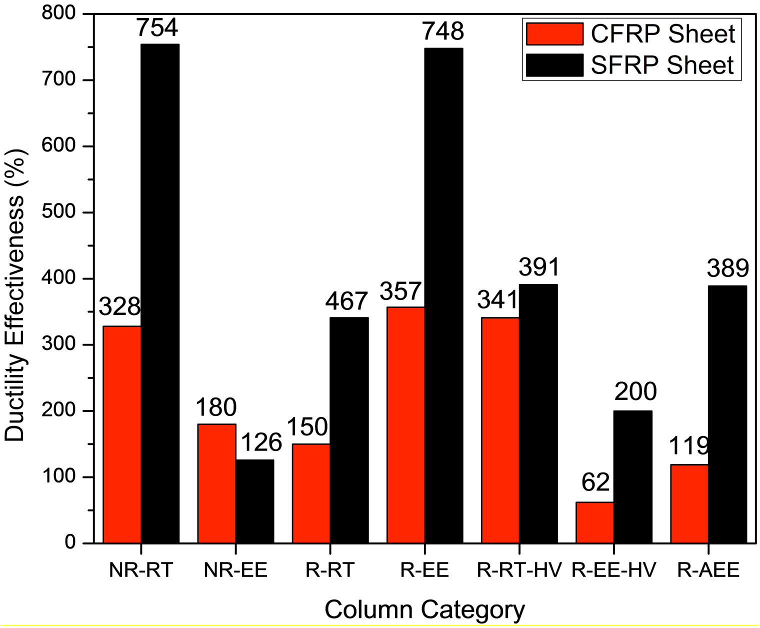

Figure 4. Ductility effectiveness of the SFRP and the CFRP wrapped columns.

5 CONCLUSION

Based on the cost and ductility effectiveness analysis, the following conclusions can be draw:

1. The CFRP wrapped unreinforced concrete (NRC) columns had higher cost effectiveness than the CFRP wrapped reinforced (RC) columns. In addition, there was an insignificant change in the cost effectiveness of the RC columns strengthened with one layer (0^{o}) and two layers ($0^{o}/90^{o}$) of the CFRP sheet.
2. The concrete columns wrapped with SFRP sheets achieved almost the same cost effectiveness with very insignificant variations. These variations were attributed to the natural variability inherited in the concrete.
3. The cost effectiveness analysis concluded that CFRP wrapped NRC columns had better performance than the SFRP wrapped NRC columns, whereas the SFRP wrapped RC columns had better cost effectiveness performance over the CFRP wrapped RC columns.
4. The ductility effectiveness had no general trend that can be recognized within the groups of CFRP and SFRP wrapped concrete columns. However, the analysis showed that regardless of the internal longitudinal reinforcement ratio, type of environmental exposure, and the FRP wrapping orientations of the columns, the ductility effectiveness of the columns wrapped with the SFRP sheets is always superior to the columns wrapped with the CFRP sheets.

Considering practical applications where concrete columns are mainly internally reinforced with longitudinal and transverse reinforcement, the cost and ductility effectiveness analysis limited to this study showed that the performance of SFRP wrapped RC columns are enhanced when compared to the conventionally used CFRP wrapped RC columns.

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