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SIZE EFFECT IN SHEAR OF CONVENTIONAL AND SHEAR-STRENGTHENED RC BEAMS WITH EB-FRP: STATE OF KNOWLEDGE AND RESEARCH NEEDS

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ABSTRACT

The size effect is known to have a major impact on shear strength of conventional reinforced concrete (RC) beams. This has been demonstrated through well documented data from numerous research studies since the 1960s. However, few studies have been conducted to investigate the size effect of RC beams shear-strengthened with externally bonded fiber reinforced polymer (EB-FRP). This is particularly relevant since the empirical equations and analytical models proposed by design guidelines for predicting the FRP contribution to shear resistance were developed on the basis of experimental laboratory test data on relatively small beams, with no consideration of the size effect. Therefore, the applicability of such models to large-size beams has not been thoroughly assessed and may well be questionable in view of some preliminary investigations. The objective of this investigation is to highlight the size effect on concrete shear strength of RC beams, either conventional or shear-strengthened with EB-FRP. The present study includes: i) extensive literature review and development of a database on the size effect; and (ii) identification and analysis of the parameters of major influence on the size effect. The research needs on the size effect of RC beams shear-strengthened with EB-FRP are also identified in this investigation.

KEYWORDS: Size effect; Reinforced concrete beams; Shear; Strengthening; Externally-bonded FRP.

INTRODUCTION

An important part of existing concrete structures were designed according to old codes and standards and therefore may present some deficiencies as far as their shear capacity, particularly with regard to the size effect on concrete shear strength. Cost-effective strengthening and rehabilitation techniques using EB-FRP composites were developed over the past two decades to extend the service life of such deficient structures and enhance their capacities. EB-FRP composites are used as an alternative to conventional retrofitting methods using externally bonded steel plates that present major drawbacks related to durability, excessive weight and handling operations.

Shear resistance of RC beams depends on several inter-related and complex mechanisms and parameters that are not understood contrary to RC beams subjected to flexural and axial loadings. This knowledge gap despite the numerous studies dedicated to the subject over more than a century is rather attributed to the complexity of the interacting parameters coming to play into the shear behavior and corresponding failure modes. This partly explains the lack of a universal approach on this subject among modern design codes and standards. The various parameters on which depends the shear strength of RC beams include the concrete compressive strength (f'_c), the longitudinal steel ratio (ρ_w) and the transverse steel ratio (ρ_s), the effective depth of beams (d), the shear span-to-effective depth ratio (a/d), as well as the size of aggregates (a_g). The contribution to shear resistance attributed to the EB-FRP for shear strengthening RC beams, which has a different behavior than concrete and steel, is another parameter that adds to that complexity.

The present study focuses on the geometry of the beams and particularly their effective depth, which give rise to the so-called "size effect" phenomenon. For conventional RC beams, the size effect has been taken into consideration in concrete shear strength models by most modern design guidelines, on the basis of results of numerous experimental studies. This is not the case for EB-FRP shear strengthened RC beams where very few investigations have been conducted so far on the size effect. Moreover, the analytical models and design equations in current guidelines, for the FRP contribution to the shear resistance, were developed based on experimental test data conducted on small specimens. Therefore, they do not take into consideration the influence of the beam size, and thus may not predict accurately the concrete shear strength of large-size beams shear-strengthened with EB-FRP composites. Thus, identifying the level of influence and developing an inclusive design model that takes into account the beam size to evaluate the contribution to the shear resistance of EB-FRP composites, is of paramount importance.

The size effect is present when there is a difference in shear stress at failure (shear strength) for geometrically similar beams of different sizes. The size effect generally results on a reduction of the shear strength as the effective depth "*d*" increases, thus associating the mechanical properties of the reinforced concrete to its geometrical properties. The size effect was associated for a long time with the brittle shear failure mechanism due to the initial defects of materials, known as the Weibull theory. The study by Kani [1] was the first that included the beam size as a variable parameter and provided a direct evidence of a strong size effect in geometrically similar beams of different sizes [2]. This was later confirmed by several studies carried out on conventional RC beams with and without internal shear reinforcement.

Research studies on the size effect of RC structures shear-strengthened with EB-FRP are relatively limited and very few [3-8]. Moreover, the maximum size of beams considered in these studies was 680 mm compared to 3000 mm in the studies on the size effect of conventional RC beams. In addition, they did not take into consideration the main parameters influencing the size effect, as considered by the studies on conventional RC structures, such as the span-to-depth ratio a/d, the size of aggregates a_g, the ratio of longitudinal tensile reinforcement ρ_w, and the concrete compressive strength f'_c. The study by Bousselham and Chaallal [7] was the only one that assessed the influence of the presence of internal steel-stirrups, ρ_s,on the size effect.

The present literature review will develop an extensive database of all experimental studies conducted in the literature on the size effect in shear of RC beams, either reinforced with steel (conventional) and FRP bars, or shear-strengthened with EB-FRP. The gathered database will be a valuable tool to identify, synthesize and evaluate the parameters of major influence on the size effect and to highlight the research needs on the size effect of RC beams strengthened in shear with EB-FRP, and to suggest targeted research focusing on the major parameters that influence the size of beams.

SIZE EFFECT

The size effect occurs when the shear strength of geometrically similar beams of different sizes decreases as the beam size increases; this has been observed by the behavior of existing large scale beams that exhibited lower concrete shear stress compared to small scale specimens carried out in laboratories. The Code development Committees generally regarded the size effect as an inconvenience that theorists were trying to impose on them [9]. There are two main types of size effect: 1) Statistical size effect (Weibull theory), which depends on the initial composition of the material such as, for example, the concrete and the position of aggregates which is random and never similar. The Weibull theory, which is associated with the initial defects of materials, is explained by Bažant and Planas [10] as a chain when the weakest link determines the strength of the whole. In this case the statistical size effect derives from the fact that the longer the chain the greater the likelihood of weak links that imply a potential low resistance; and 2) Fracture mechanics size effect, based on the theory of energy release during the development of cracks. This theory represents the only significant theory applicable to concrete, which is adopted by all experimental studies.

Bažant and Planas [10] proposed a law that takes into consideration the size effect on shear strength of structures, which has been validated by a very large number of experimental tests, as follows:

$$\sigma_{Nu} = \frac{Bf'_t}{\sqrt{1+D/D_0}} \qquad (1)$$

Where f'_t : the tensile strength of the material, B: a dimensionless constant (geometry-dependent parameter) and D_0: a constant (size-dependent parameter) with the dimension of length. Both B and D_0 depend on the fracture properties of the materiel and on the geometry of the structure, but not on the structure size.

According to Syroka-Korol [11]: “the size effect phenomenon in quasi-brittle structures is related to a transition from a ductile behaviour of small specimens to a totally brittle response of large ones.”

In what follows, analysis of database parameters will be expressed:

i) either by normalized shear strength, $v_n = \frac{V_T}{b_w d\sqrt{f'_c}}$, where V_T = experimental shear resistance in N; b_w= widh of beam in mm; d = effective depth of beam in mm and f'_c = concrete compressive strength in MPa;

ii) or percentage of shear strength loss, $\left(1 - \frac{v_{nd}}{v_{np}}\right) * 100$, where v_{nd} = normalized shear stress of large scale beam with effective depth d and v_{np} = normalized shear stress of reference beam (small scale beam from the same series).

REVIEW AND SYNTHESIS OF PREVIOUS WORK

For decades, researchers conducted studies on small specimens in laboratories to study the behavior of RC beams, for obvious reasons related to cost of materials, testing equipment and time of implementation. However, once it became apparent that the size effect may have a major impact on concrete shear strength of RC structures, the effective depth of beams d became a key parameter of study when investigating the shear behavior. Figure 1 presents histograms of the percentage of test data as a function of d for all the research studies conducted on the size effect in shear of RC beams. The results revealed that 76% of available experimental data are based on specimens with d less than 700 mm. Moreover, just 6% of all studies corresponded to RC beams strengthened in shear with EB-FRP, in which 77% consisted of *d* less than 500 mm. This clearly highlights the distinct lack of research on the subject and the need for more size effect studies on larger sizes of RC beams shear-strengthened with EB-FRP composites.

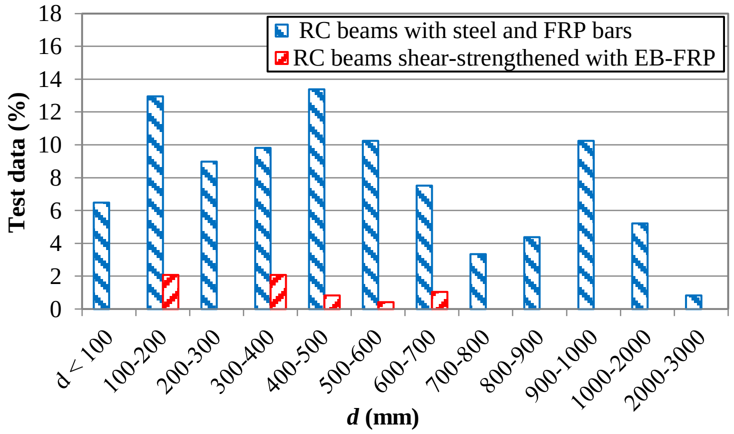


Figure 1: Distribution of test data on size effect as a function of d (in percentage)

The size effect in shear of conventional RC beams is relatively well documented. It has been assessed by many researchers since the 1960s. Five parameters have been identified in the literature to have major impact on the size effect in shear strength: 1) the nominal size of aggregates (a_g) that governs the mechanical action of the aggregate interlock; 2) the concrete compressive strength (f'_c) ; 3) the ratio of longitudinal tensile reinforcement (ρ_w) that governs the dowel action; 4) the ratio of transverse steel reinforcement (ρ_s) that influences the diagonal shear crack patterns (spacing and opening); and 5) the shear span-to-effective depth ratio (a/d) that defines the slenderness of the beam.

An extensive database of all available experimental studies on the size effect in shear of concrete beams with reinforcing steel and FRP bars, steel fiber-reinforced concrete (SFRC) beams, and RC beams shear-strengthened with EB-FRP was developed in the present study and is presented in Table 1. It includes all the properties and configuration of specimens (geometry and type of beams) and the study parameters of major impact (a/d, a_g, f'_c, ρ_w, ρ_s and ρ_{FRP}). Note that the number of specimens shown in the table represents the tests that were deemed valid, unambiguous and non-repetitive or irrelevant. Overall, 478 specimens from 48 studies were selected.

From Table 1, the following observations can be made: 1) very few studies evaluated the size effect on RC beams shear-strengthened with EB-FRP; 2) only one study considered the full wrap configuration for shear strengthening with EB-FRP; 3) the majority of specimens consisted of rectangular beams; 4) only one study considered pre-cracked RC beams; and 5) none of the parameters of major influence on size effect had been assessed by the studies on RC beams strengthened with EB-FRP, except for the transverse steel ratio (ρ_s) considered in just one study.

Details of all the 478 specimens of studies, as numbered in Table 1, are also provided as an appendix in Table A.1 (RC beams reinforced with steel and FRP bars) and Table A.2 (RC beams shear-strengthened with EB-FRP). It includes: 1) the geometry and type of beams (b, d, a/d); 2) properties and ratios of all materials (a_g, ρ_w, ρ_s, ρ_{FRP}, ρ_s and f'_c); and 3) the experimental results (total shear resistance, V_T and resistance due to EB-FRP, V_{FRP}). In-depth analysis of these tables made it possible to distinguish the studies according to the parameters of major influence on the size effect, as presented in the following sections.

Figure 2 presents the distribution of test specimens, in percentage, according to the different parameters of major impacts on the size effect. Every set of histograms for each parameter represents the entire 478 test specimens considered, corresponding to 100%. The most important findings are as follows: 1) For each parameter, the number of tests on RC beams shear-strengthened with EB-FRP is very few or even negligible; 2) Just 9% of all tests consisted of T-section specimens despite the fact that most RC structures, including bridges, are built with T-section beams; 3) 78% of the tested RC beams (i.e., 374 specimens) were without any internal shear reinforcement.

Table 1. Summary of experimental research on size effect of RC beams

		Properties and parameters

				Geometry							Type of beam				Study parameters					Shear strengthening with EB-FRP					
	Author	**Year**	**No. of specimens**	**Rectangular section**	**T-Section**	$d \leq 200$ **mm**	$200 < d \leq 450$	$450 < d \leq 700$	$700 < d \leq 1000$	$d > 1000$ **mm**	$a/d \leq 1$	$1 < a/d < 2.5$	$a/d \geq 2.5$	**Pre-cracked beams**	a/d	f_c'	ρ_w, ρ_{FRP}	ρ_s	a_g	**U-wrap**	**Full wrap**	**Continuous**	**Strips**	**One layer**	**Multiple layers**
Conventional RC beams	Leonhardt and Walther [1]	1962	8	■		■	■	■					■				■								
	Kani, GNJ	1967	22	■		■	■	■	■		■	■	■		■										
	Bhal [1]	1968	6	■			■	■	■	■			■				■								
	Swamy and Shamsuddin	1971	26		■	■						■	■		■			■	■						
	Taylor, HP	1972	8	■		■	■	■	■				■						■						
	Walraven, Joost C [1]	1978	3	■		■	■	■	■				■												
	Chana, PS	1981	4	■		■	■						■						■						
	Iguro et al.	1985	7	■		■	■	■	■	■		■							■						
	Niwa, Yamada [2]	1987	3	■						■			■				■								
	Bazant and Kazemi	1991	5	■		■	■						■												
	Walraven and Lehwalter	1994	19	■		■	■	■	■		■		■					■							
	Grimm, R [2]	1997	6	■		■	■	■	■				■				■								
	Gannoum	1998	24	■		■	■	■	■				■			■	■		■						
	Podgorniak-Stanik [2]	1998	6	■		■	■	■	■				■			■									
	Collins and Kuchma	1999	25	■		■	■	■	■				■			■	■								
	Tan and Lu	1999	12	■			■	■	■	■	■	■			■										
	Kotsovos and Pavlovic	2001	16	■		■	■	■					■				■	■							
	Fujita et al.	2002	9	■			■	■	■				■			■									
	Yang et al.	2003	16	■			■	■	■		■	■			■	■									
	Bentz and Buckley	2005	9	■		■	■						■												
	Zhang and Tan	2007	12	■			■	■	■			■			■			■							
	Yang, K H	2007	12	■			■	■			■	■				■									
	Zakaria et al.	2009	4	■		■	■	■				■	■		■										
	Sneed and Ramirez	2010	8	■			■	■	■				■												
	Yu et al.	2011	6	■			■	■	■	■			■												
	Kim et al.	2013	15	■			■	■					■												
	Yu et al.	2013	6	■			■	■	■	■			■												
	Arun and Ramakrishnan	2014	9	■			■	■					■			■	■	■							
	Syroka-Korol and Tejchman	2014	6	■		■	■	■	■		■		■		■		■								
	Birrcher et al.	2014	9	■				■	■	■		■	■		■										
	El-Sayed and Shuraim	2016	12	■			■	■	■		■					■									
SFRC	Minelli et al.	2007	9	■				■	■				■			■		■							
	Minelli et al.	2014	9	■			■	■	■	■			■												
	Shoaib et al.	2014	12	■			■	■	■				■			■	■								
FRP bars	Massam [3]	2001	6	■		■	■	■	■				■				■								
	Matta et al.	2007	4	■					■				■				■	■							
	Bentz et al.	2010	11	■		■	■	■	■				■				■	■							
	Alam and Hussein	2012	6	■			■	■					■				■								
	Matta et al.	2013	4	■			■	■	■				■				■								
	Alam and Hussein	2013	12	■			■	■	■				■				■								
	Ashour and Kara	2014	6	■		■	■						■				■								
	Mahmoud and El-Salakawy	2016	12	■			■	■	■				■			■	■								
EB-FRP	Deniaud and Cheng	2001	6		■		■	■					■							■		■		■	
	Qu et al.	2005	6	■		■	■	■				■								■			■		■
	Leung et al.	2007	9	■		■	■	■					■							■	■		■		■
	Godat et al.	2010	6	■		■	■	■				■								■			■		■
	Bae et al.	2012	6	■			■	■					■							■			■	■	
	Bousselham and Chaallal	2013	12		■	■	■						■					■		■		■		■	■
	Nguyen-Minh and Rovňák	2015	15	■		■	■	■				■		■						■		■			■

Note : The number of specimens shown in the table represents tests that are deemed valid, unambiguous and non-repetitive or irrelevant; Results are taken from the study by: [1]Zararis and Papadakis [12], [2]Reineck and Kuchma [13], [3]Matta [14]; The study by Godat [15] is a numerical modelling of the specimens tested by Qu [4].

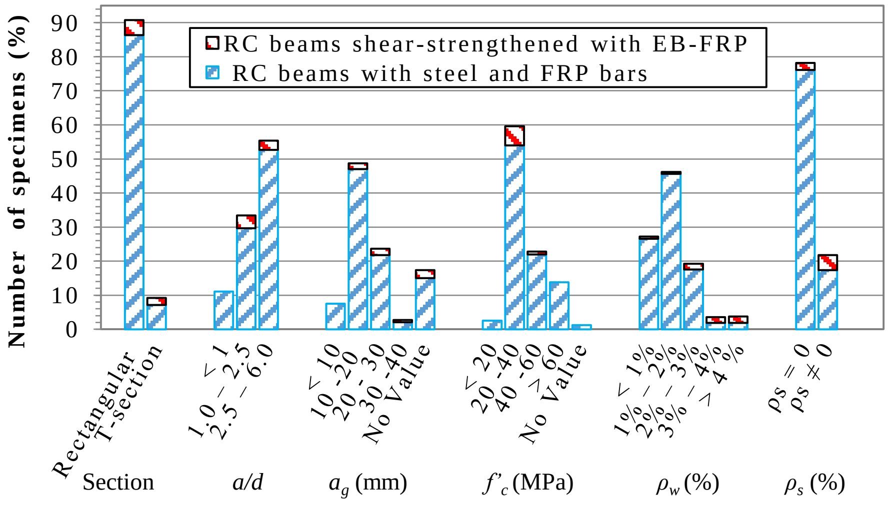


Figure 2: Distribution of test data on size effect for each study parameter (in percentage)

PARAMETERS OF MAJOR INFLUENCE ON SIZE EFFECT

Figure 3 shows the number of test specimens according to each parameter that was considered as a study parameter, in order to evaluate its influence on the size effect. Of those tests, 174 specimens (18 studies) varied the ratio of longitudinal reinforcement (ρ_w, ρ_{FRP}), 143 specimens (11 studies) examined the influence of the concrete compressive strength (f'_c), 103 tests (7 studies) evaluated the impact of shear span-to-effective depth ratio (a/d), 94 specimens (9 studies) varied the ratio of transverse steel (ρ_s), and finally 69 specimens (5 studies) considered the size of aggregates (a_g) as a study parameter. It should be noted that in all the studies on RC beams shear-strengthened with EB-FRP, only the addition of the FRP was assessed as a study parameter without taking into consideration all the other parameters of major impact. Except Bousselham and Chaallal [7] who evaluated the influence of internal transverse steel (ρ_s) on the size effect, as shown in the figure. Refer to Table 1 for the corresponding authors of each study parameter.

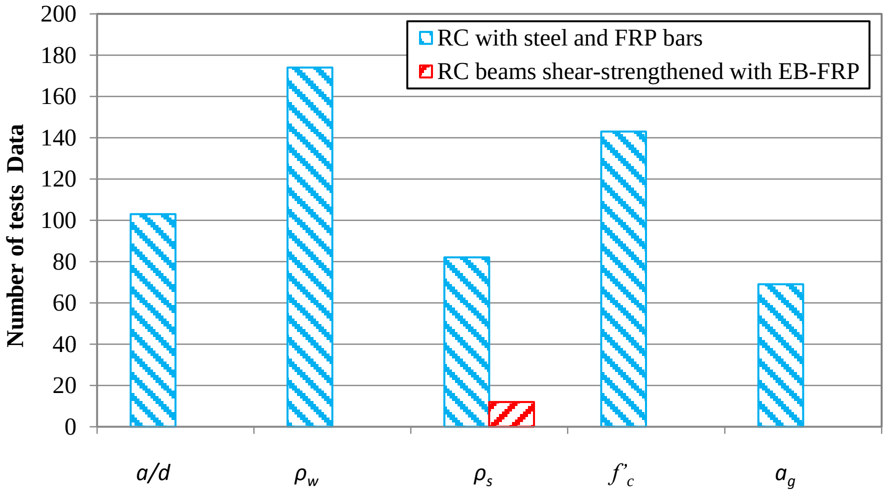


Figure 3: Distribution of specimens that assessed the influence of each parameter on size effect

Size of aggregates (a_g)

The database shows that the majority of studies on the size effect considered the same ratio of materials (ρ_w, ρ_s, ρ_{FRP}) for the same series of geometrically similar RC structures of different sizes, except for the size of aggregates (a_g), where the researchers kept the same a_g for the whole series of specimens. However, just five studies (69 specimens) considered "a_g" as a study parameter of major influence on the size effect of RC beams. In fact, only the studies conducted by Swamy and Shamsuddin [16], Taylor [17] and Chana [18] have scaled the aggregates simultaneously with increasing the effective depth "*d*" by keeping the same ratio (a_g/d), as shown in Table 2. Iguro [19] have increased the size of aggregates from 10 mm to 25 mm for each increase in "*d*" (from 600 mm to 1000 mm and from 1000 mm to 2000 mm). However, Ghannoum [20] considered two series of specimens with two different sizes of aggregates each (a_g = 10 and 20 mm), resulting in a gradual decrease in the ratio (a_g/d) with increasing "*d*" between 65 mm and 870 mm.

The size of aggregates governs the mechanism of aggregate interlock and, hence, contributes significantly to the shear resistance of cracked RC beams. This has been evaluated by Fenwick and Paulay [21] as the most important parameter influencing the load carrying capacity, which contributes to 70% of the total shear resistance. According to Taylor [17], when the size of aggregates is properly scaled with the increase in beam's size, the decrease in concrete shear strength due to size effect becomes negligible. Swamy and Shamsuddin [16] revealed that the increase in concrete shear strength with increasing "a_g" is partially due to the enhancement in aggregate interlock. This was observed in the results by Iguro [19], where the loss in shear strength of RC beams without shear reinforcement with increasing "*d*" was reduced by half (from 32% to 16% loss) when increasing a_g from 10 mm to 25 mm in the larger beam (d = 1000 mm) (see Table 2).

Moreover, despite the scaling of a_g, the results in the table showed an increase in shear strength loss with increasing the beam's size, hence demonstrating the existence of a size effect. However, no (or negligible) size effect was observed in some specimens when doubling d with a_g [16, 19]. Therefore, it can be deduced that the size effect may be suppressed provided that a good correlation between the size of aggregates and the depth is established for a given beam.

It should be mentioned that this parameter of major influence on the size effect was not evaluated in any of the studies carried out on RC beams shear-strengthened with EB-FRP composites. However, other than the tension stress exerted by the externally bonded fibers to resist the shear force of specimens, the FRP wrapping can provide confinement to the cracked concrete, hence increasing the shear capacity [22]. A better confinement reduces the opening of shear cracks, enhances thereby the aggregate interlock mechanism and, consequently, mitigates the size effect of RC beams.

Table 2. Influence of aggregate size "a_g" on the size effect

	Swamy (1971)			Taylor (1972)				Chana (1981)				Iguro (1985)			
d (mm)	57	86	171	140	232	465	930	42	106	177	356	600	1000	1000	2000
a_g (mm)	6.35	9.5	19	2.4	9	19	38	2.4	5	10	20	10	10	25	25
a_g/d	0.11	0.11	0.11	0.02	0.04	0.04	0.04	0.06	0.05	0.06	0.06	0.017	0.010	0.025	0.012
Loss[1]	-	14.9	14.1	-	8.3	15.5	20	-	23.6	37.1	54.4	-	32	16	35

Note : [1] Loss in shear strength (%)

Longitudinal tensile reinforcement (ρ_w, ρ_{FRP})

The longitudinal reinforcement contributes to the total shear resistance by its tension force and the dowel action mechanism, which is generated right at the shear crack. The dowel action depends mainly on the diameter of longitudinal reinforcement, the concrete cover and the presence of transverse shear reinforcement [23].

Taylor [17] revealed that the dowel action contribution to the total shear resistance of RC beams without transverse steel is between 15% and 25%. According to the author, the contribution to shear resistance due to dowel action is significantly associated with the layout of longitudinal reinforcement (one or more layers). In fact, the dowel action of a beam with two layers of two reinforcing bars each was only 40% greater than that with one layer of two bars of the same diameter. Moreover, the longitudinal steel bars, ρ_w, distributed along the entire depth of the beam has also an impact on the behavior of RC beams by increasing their shear strength. Collins and Kuchma [24] examined two series of geometrically similar beams without internal transverse steel; the first series with equally spaced layers of crack control longitudinal steel reinforcement and the second without. The results showed a decrease in shear strength with increasing "*d*" for the second series of specimens, whereas almost the same resistance was obtained in those of the first series. For instance, a loss of 27% (f'_c = 86 MPa) and 14% (f'_c = 50 MPa) in resistance was obtained in the specimens compared respectively to 4% (f'_c = 86 MPa) gain and 5% (f'_c = 50 MPa) loss in those with distribution of reinforcing bars. This could be attributed to the fact that the distribution of longitudinal steel bars along the entire depth prevents the development of diagonal shear cracks, hence resulting in enhanced resistance with increasing "*d*". Therefore, it can be concluded that the enhancement in shear behavior due to the distribution of bars over the beam depth may have a positive impact in mitigating the size effect.

Zakaria [25] stated that for larger beams, greater spacing, and hence wider, diagonal shear cracks occurs when increasing "*d*", due to the reduced capacity of the longitudinal reinforcement to control the crack spacing; in fact, as the distance from mid-height of the beam to the reinforcing bars increases, the crack spacing becomes larger. Moreover, the ratio of longitudinal reinforcement (ρ_w) has an inversely proportional relationship with the spacing/opening of cracks; an increase in the amount of reinforcing bars enhances the shear mechanism by decreasing the crack spacing, which results in smaller openings. This indicates that the size effect can be mitigated by the smaller cracks in increasing the amount of longitudinal reinforcement.

Figure 4 illustrates the normalized shear strength as a function the amount of longitudinal steel reinforcement (ρ_w). It includes all the studies that investigated the influence of ρ_w on the size effect of RC beams (Table 1). The results revealed an increase in shear strength as ρ_w increases.

All the studies on concrete structures with reinforcing FRP bars showed the existence of a size effect, which seems to be similar to that of RC beams with steel bars. Figure 5 presents the variation of the shear strength with increasing the beam's size, for the specimens that evaluated the influence of the ratio of longitudinal FRP bars (ρ_{FRP}) on the size effect. The figure showed a decrease in strength as "*d*" increased, whereas for the same series of specimens, an increase in shear strength occurred when increasing ρ_{FRP}. This clearly demonstrates the existence of a size effect, which can be significantly mitigated with the increase in ρ_{FRP}, as in the case of studies by [14, 26]. According to Alam and Hussein [27], the size effect is even more pronounced in beams with reinforcing internal FRP bars than in beams with steel bars.

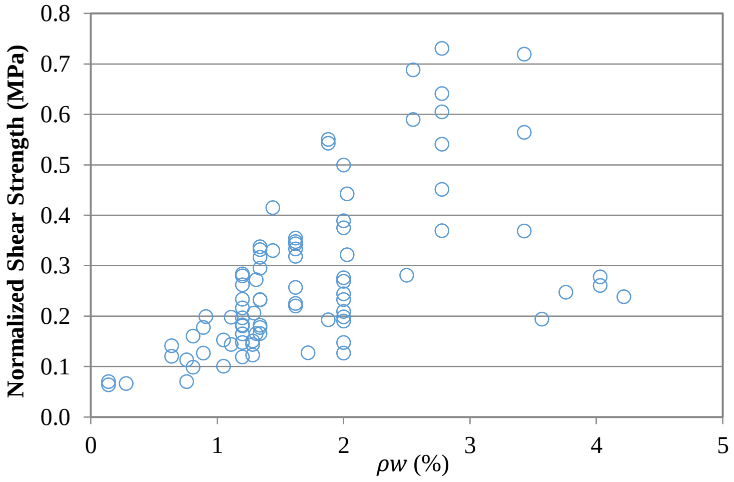


Figure 4: Variation in shear strength of RC beams with increasing longitudinal steel ratio ρ_w

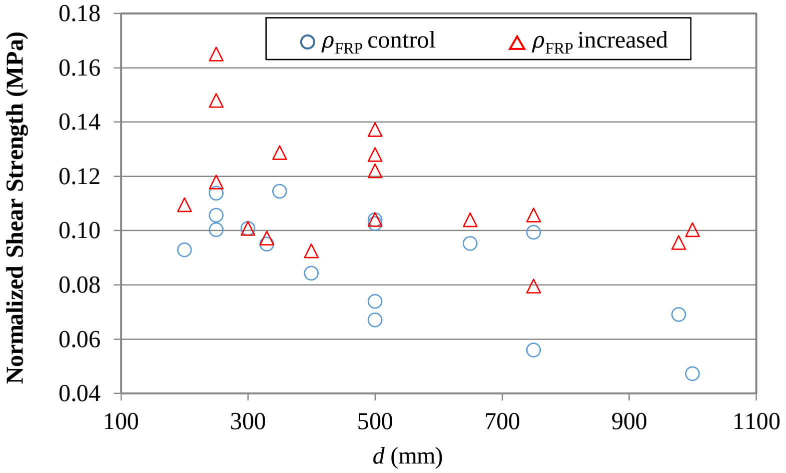


Figure 5: Influence of ρ_{FRP} ratio on the size effect of beams with reinforcing FRP bars

Concrete compressive strength (f'_c)

The concrete stress-strain response shows that the increase in the concrete compressive strength, f'_c, from normal-density to high-density (between 20 and 100 MPa) decreases its ductility, which results in a more brittle failure. A high resistance concrete drives the shear cracks to pass through the aggregates instead of bypassing them, because the resistance of cement paste exceeds that of aggregates, generating a smoother surface plane of cracks. According to El-Sayed and Shuraim [28], smoother surface cracks decrease the aggregate interlock. However, as explained earlier in section-*Size of aggregates*, an increase in the size of aggregates leads to rougher crack surface, which results in an aggregate interlock enhancement that tends to mitigate the size effect. Therefore, it can be concluded that increasing the concrete compressive strength has a negative impact since it amplifies the size effect of RC beams.

Figure 6 presents the influence of the concrete compressive strength, f'_c, on the normalized shear strength with increasing the effective depth "*d*". The figure included the studies that investigated "f'_c" as a study parameter where all the specimens were slender type RC beams without internal shear reinforcement (Table 1). The results revealed that the resistance of RC beams is inversely proportional to f'_c and *d*. In fact, a decrease in shear strength occurred with the increase in f'_c and/or the increase in beam's size. Moreover, a 14% loss in shear strength was obtained when doubling "*d*" (from 460 mm to 920 mm) for $f'_c = 50$ MPa compared to 27% loss in the same specimens for $f'_c = 90$ MPa. This demonstrates that the size effect was influenced by "f'_c", and is more pronounced at high resistance concrete beams. The same was also demonstrated by Fujita [29] who stated that the size effect became more significant with a greater effective depth and a greater concrete compressive strength.

There are no studies that assessed the influence of f'_c on the size effect of RC beams strengthened in shear with EB-FRP. Although some design codes and standards have recommended an upper limits for f'_c when designing RC structures retrofitted with EB-FRP (e.g., CSA S806-12 [30] where $f'_c \leq 80$ MPa), these limitations seem to be insufficient to suppress the size effect since it was demonstrated that it exists even for values of f'_c much smaller than 80 MPa. Therefore, the procedures for shear design calculations of RC beams shear-strengthened with EB-FRP should take into consideration the influence of f'_c on the size effect, which is not yet captured in current guidelines and codes.

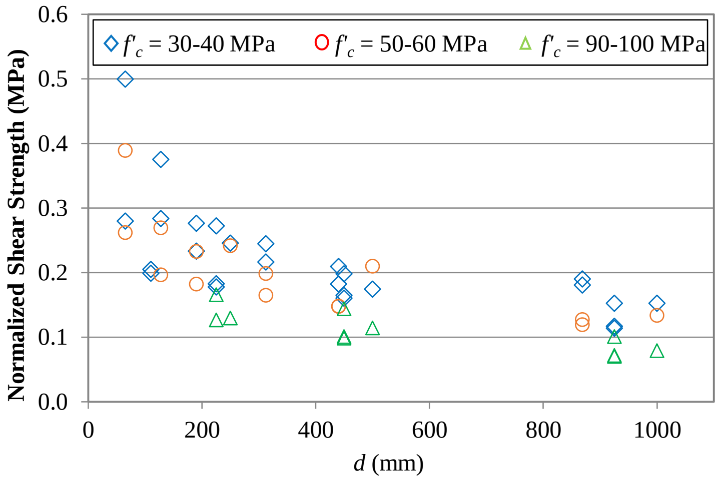
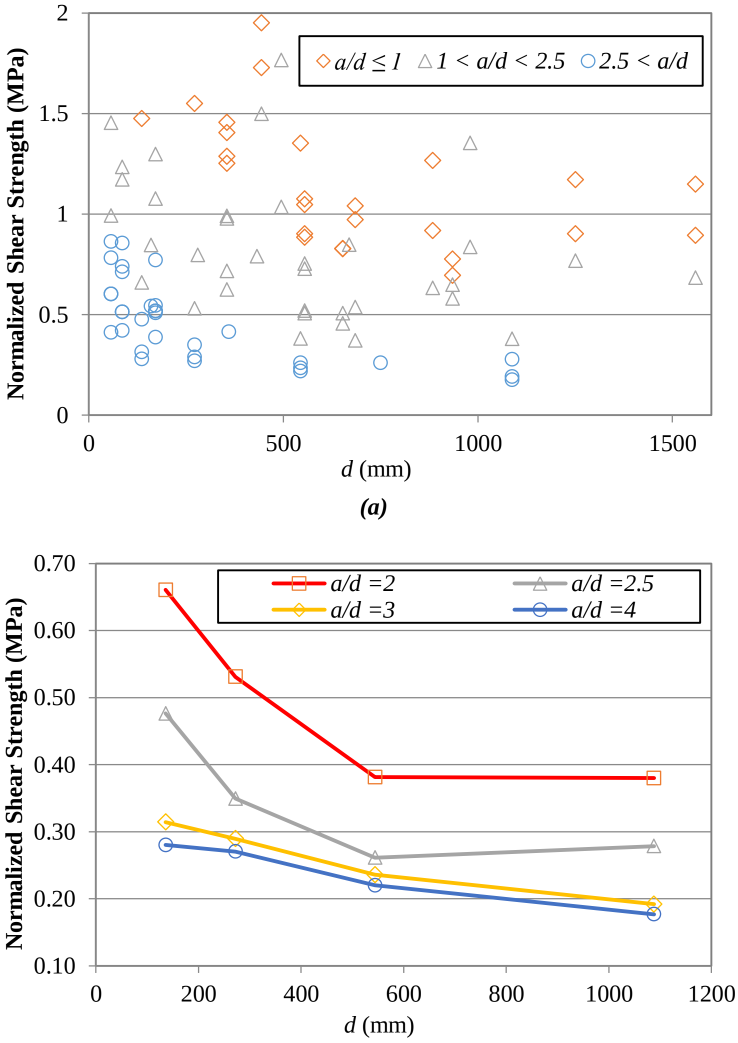


Figure 6: Influence of f'_c on the size effect of RC beams

Shear span-to-effective depth ratio (*a/d*)

Figure 7(a) illustrates the influence of shear span-to-effective depth ratio (*a/d*) on the shear strength of RC beams for the studies that varied (*a/d*) as a study parameter to assess the size effect (Table 1). The results revealed the existence of a size effect in shear for all tested specimens, where both the slender and deep beams exhibited a decrease in shear strength while increasing the effective depth "*d*". In addition, the shear strength of RC beams has been inversely proportional to ratio (*a/d*); in fact, for the same beam's size "*d*", the specimens exhibited lower levels of resistance with greater values of (*a/d*), particularly for slender beams. Also, it was noted that the size effect was more pronounced in deep beams compared to slender ones; where higher loss rate in the shear strength was observed with increasing "*d*", in particular for beams with a size $d < 700$ mm.

Figure 7(b) presents the variation in shear strength of RC beams without internal transverse steel according to several values of ratio (*a/d*) by Kani [1]. The results showed a more pronounced size effect with the decrease in (*a/d*), especially for deep beams, where a significant loss in shear strength occurred with increasing "*d*". This holds true for an effective depth "*d*" less than 550 mm, whereas no size effect was observed for deep beams beyond this value. This was later confirmed by Tan and Lu [31] who revealed that the critical depth of deep beams, beyond which the size effect becomes insignificant and seems relatively independent of the ratio (*a/d*), is between 500 and 1000 mm. However, for slender beams with higher values of (*a/d*), the curves show a quasi-linear response of size effect, where a decrease in shear strength occurred with increasing "*d*", regardless of the beam's size. Moreover, in all tested specimens, lower levels of resistance were obtained in slender beams compared to deep beams, as the ratio (*a/d*) increased.



(a)

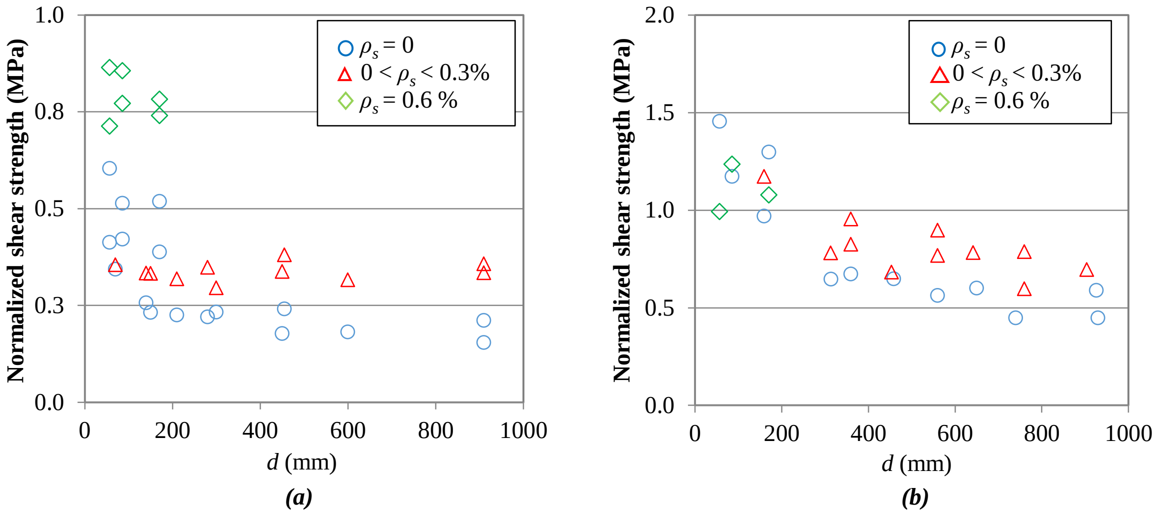
(b)

Figure 7: Influence of shear span-to-effective depth ratio (a/d) on the size effect

Transverse steel reinforcement (ρ_s)

Experimental tests showed that the presence of internal shear reinforcement significantly increases the shear strength of RC beams, and hence mitigates the size effect. The fact that the resistance of steel stirrups is greater than that of concrete tends to overshadow the size effect on total shear resistance [7]. This is attributed to the fact that the transverse steel enhances the aggregate interlock by preventing the diagonal shear cracks to widen, and thus reduces the size effect. For instance, the loss in shear strength with increasing the beam's size decreased from 36% to 2% in the tests performed by Kotsovos and Pavlovic [32] on RC beams without and with internal transverse steel (ρ_s = 0.25%), respectively. Yu and Bažant [33] revealed that although the transverse steel mitigates the size effect, it cannot be completely suppressed regardless of the amount of steel-stirrups.

Figure 8 presents the variation in shear strength of slender (Figure 8(a)) and deep (Figure 8(b)) RC beams with increasing the effective depth "*d*", as a function of the presence and increase in transverse steel ratio (ρ_s). It includes the studies that considered (ρ_s) as a study parameter to assess the size effect (Table 1). The results revealed the existence of a size effect in all series of tested specimens without internal shear reinforcement (ρ_s = 0), where both the slender and deep beams exhibited a significant loss in shear strength while increasing the beam's size. However, the addition of steel-stirrups reduced the size effect where lower loss rate in the shear strength occurred with increasing "*d*". In fact, for the same series of specimens, a considerable increase in shear resistance occurred with the presence of ρ_s, especially in slender beams of larger sizes.



(a) ***(b)***

Figure 8: Influence of transverse steel ratio ρ_s on the size effect: a) Slender beams; b) Deep beams

Analysis of the literature data revealed that the use of steel fibers in RC (SFRC) structures better control and stabilize the shear crack propagation. This may be attributed to the homogeneous distribution of steel fibers into the entire concrete section, hence influencing the size effect. In fact, studies on the size effect of SFRC beams [34-36] have shown that steel fibers could mitigate the size effect if provided in sufficient quantities. Also, the authors demonstrated that SFRC beams have a similar shear behavior as that of RC beams with the minimum amount of internal transverse steel. Shoaib [36] demonstrated that the replacement of the minimum shear reinforcement amount with steel fibers in RC beams where $h \leq 600$ mm and $f'_c \leq 40$ MPa, as required by the ACI 318-14 [37] code, can also be applicable for larger beams (up to 1000 mm depth) and higher concrete compressive strength (up to 80 MPa).

The histograms in Figure 9 illustrate the variation of shear strength with increasing "*d*" according to the presence and increase of steel fibers ratio (ρ_{SFRC}) in RC beams for the study by Minelli [34]. A significant increase in shear resistance was obtained with the addition of steel fibers. In addition, the results showed the existence of a size effect in SFRC beams for a depth "*d*" less than 940 mm, beyond which the size effect becomes insignificant. Moreover, it is observed that the increase in the amount of steel fibers has reduced the size effect; for instance, an increase in ratio ρ_{SFRC} from 0.64% to 1% reduced the loss in shear strength respectively from 42% to 23%, while increasing "*d*" from 440 to 940 mm.

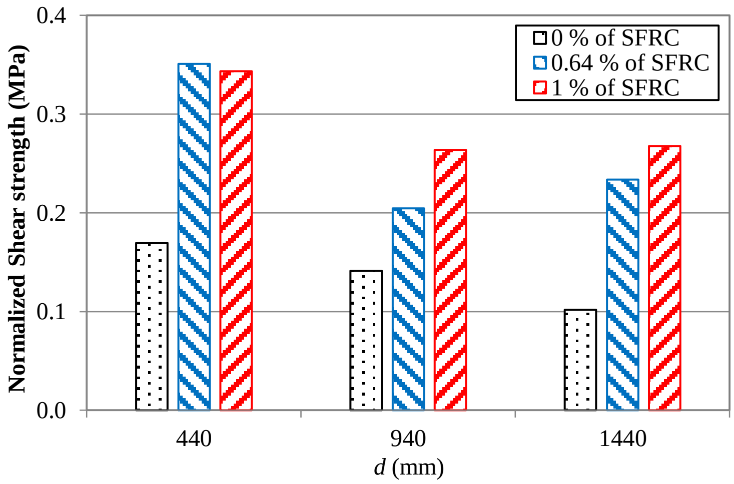
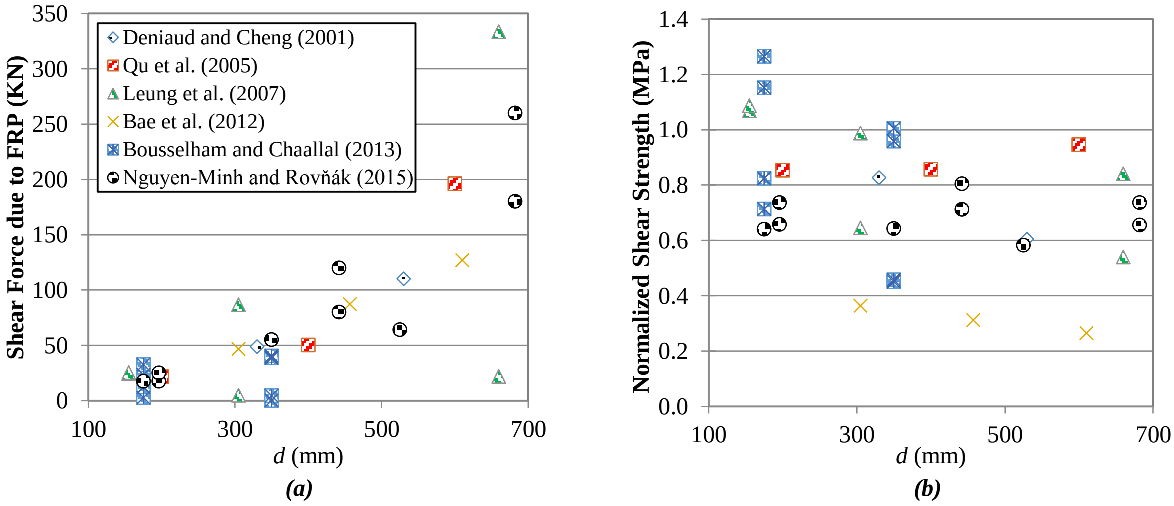


Figure 9: Influence of steel fibers on the size effect of RC beams

The shear behavior of RC beams strengthened in shear with EB-FRP with internal shear steel reinforcement is quite different than those without, which is due to the interaction between internal transverse steel and EB-FRP. This interaction tends to decrease the gain contribution to shear resistance due to FRP with the presence and increase in transverse steel ratio (ρ_s). However, despite the major influence of ratio ρ_s on the size effect of RC beams, only the study by Bousselham and Chaallal [7] on shear strengthening with EB-FRP considered ρ_s as a study parameter, in order to assess its influence on the size effect of retrofitted RC beams. The authors found that strengthened specimens without internal steel stirrups (ρ_s = 0) exhibited a 37% loss in shear strength by doubling the beam's depth from 175 mm to 350 mm, whereas the loss was reduced to 14% after the addition of steel stirrups (ρ_s = 0.37%). This confirms the findings of other researchers, as already observed on conventional RC beams, that the presence or increase in internal transverse steel ratio tends to reduce the size effect, but cannot eliminate it completely.

SIZE EFFECT OF RC BEAMS SHEAR-STRENGTHENED WITH EB-FRP

Investigations on size effect on RC beams strengthened in shear with EB-FRP are significantly fewer than those of conventional RC beams. Figure 10(a) illustrates the shear force at failure due to FRP, V_{FRP}, with increasing the beam's size for the studies conducted on specimens shear-strengthened with EB-FRP (Table 1). The results show that the contribution in the shear resistance due to FRP increased with "*d*" for the same series of tested specimens. This can be attributed to the fact that the increase in beam's height increases the effective bond and anchorage length of FRP composites, hence increasing their contribution to shear resistance. However, as shown in Figure 10(b), a decrease in the normalized shear strength was obtained with the increase in "*d*" for the same series of specimens, except for the study by Qu [4], confirming the existence of a size effect in shear for RC beams strengthened in shear with EB-FRP.



(a) ***(b)***

Figure 10: Size influence of RC beams shear-strengthened with EB-FRP: a) Shear force; b) Normalized shear strength

Deniaud and Cheng [3] carried out tests on two different sizes (400 and 600 mm depths) of T cross-section beams with internal transverse steel (ρ_s = 0.1%). The specimens were shear-strengthened in shear with EB-GFRP sheets using U-wrap configuration in a single layer (ρ_{FRP} = 2.6%). The authors revealed that the size of specimen significantly influences the FRP shear behavior of RC beams. In fact, the results showed a 27% loss in shear strength in the GFRP strengthened specimens with increasing the beam's size, whereas a 40% loss was obtained in the non-strengthened RC specimens. This indicates that the use of FRP for shear strengthening had a positive impact on the shear behavior of large scale RC beams by reducing the size effect.

Qu [4] carried out tests on three different sizes of rectangular beams (200, 400 and 600 mm depths). The specimens were shear-strengthened with EB-CFRP sheets using U-wrap configurations in one, two and three layers according to the increase in beam's size, while keeping the same ratio of FRP (ρ_{FRP} = 0.13%). All tested specimens were without internal shear reinforcement. The results showed a negligible size effect due to the FRP strengthening system when comparing the smallest beam with the largest one. Indeed, an 11% gain in shear strength was obtained in the CFRP strengthened specimens compared to 14% gain in the non-strengthened ones. The authors found that the contribution to shear resistance due to FRP is divided into a direct contribution (V_{FRPd}) and an indirect contribution (V_{FRPi}). V_{FRPd} represents the summation of shear forces in FRP strips calculated based on the recorded strains, whereas V_{FRPi} represents the enhancement in FRP contribution to the shear resistance, due to the decrease in inclination of shear crack angles and the enhancement in aggregate interlock mechanism. The authors found that the direct contribution has little or no impact on the size effect, which is mainly attributed to the indirect shear contribution of FRP.

Leung [5] carried out tests on three different sizes of rectangular beams (180, 360 and 720 mm depths) with internal steel-stirrups (ρ_s = 0.28%). The specimens were shear-strengthened with EB-CFRP sheets using U-wrap and full-wrap configurations; one, two and four layers of EB-CFRP were considered while doubling the beam's size, in order to keep the same FRP ratio (ρ_{FRP} = 0.1%). The results revealed a 23% loss in shear strength for conventional RC specimens (non-strengthened) with increasing the beam's size from 180 to 720 mm. For comparison, a loss of 50% was obtained for the same series of specimens after strengthening in shear with U-wrap EB CFRP sheets, versus 23 % loss for the full-wrap strengthened specimens. This indicates the existence of a significant additional size effect due to the EB-FRP shear strengthening system using U-wrap configuration without anchorage, whereas no size effect was observed in the full-wrap system.

Bae [6] carried out tests on three different sizes of rectangular beams (370, 550 and 700 mm depths) without internal shear reinforcement. The specimens were shear-strengthened with EB-CFRP U-wrap sheets in one layer (ρ_{FRP} = 0.05%). The results revealed the existence of an additional size effect of RC beams due to FRP shear strengthening system. In fact, a 27% loss in shear strength was obtained in CFRP strengthened specimens while increasing the beam's size from 370 to 700 mm, compared to an 18% loss in the non-strengthened specimens.

Bousselham and Chaallal [7] carried out tests on two different sizes of T-section beams (220 and 406 mm depths) with two ratios of internal transverse steel (ρ_s = 0 and 0.375%). For both sizes, the specimens were shear-strengthened with EB CFRP using U-wrap sheets in one and two layers (ρ_{FRP} = 0.14 and 0.28%), in order to evaluate the influence of FRP rigidity on the size effect. Figure 11 illustrates in histograms, for each series of tested RC T-beams, the loss in shear strength with increasing beam's size due to the addition of FRP and increase in FRP ratio. As shown, for specimens without internal shear reinforcement, the loss in strength increased from 30% in conventional (non-strengthened) specimens to 37% in specimens strengthened with one layer of CFRP to reach 45% in those with two layers while doubling the CFRP rigidity. In addition, for the same series of specimens, the loss in shear strength dropped to more than half with the addition of internal steel-stirrups (12% in non-strengthened specimens, 17% and 21% in strengthened specimens respectively with one and two layers), thus keeping the same rate of resistance loss. This indicates that an additional size effect exists due to the EB-CFRP shear strengthening system, which becomes more evident with the increase in CFRP rigidity.

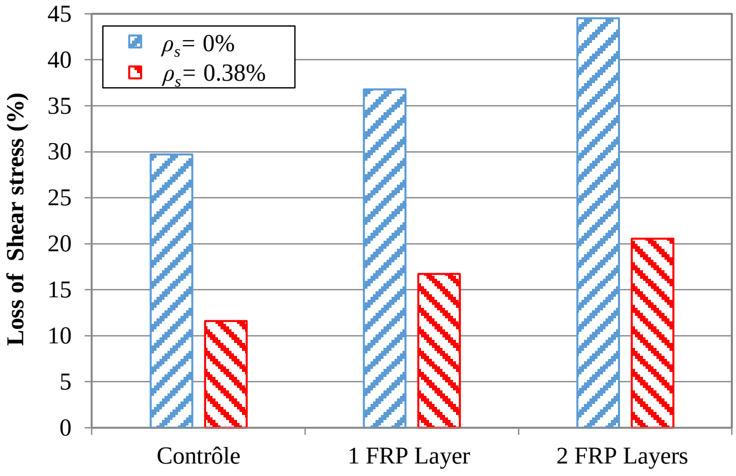


Figure 11: Loss in shear strength with increasing beam size due to FRP

Nguyen-Minh and Rovňák [8] conducted two series of tests on RC rectangular beams with internal transverse steel (ρ_s = 0.17%). The first series consisted of three sizes of specimens (200, 400 and 600 mm depths) strengthened in shear with EB-GFRP, whereas the second series consisted of pre-cracked specimens of three different sizes (250, 500 and 750 mm depths) shear-strengthened with EB-GFRP and EB-CFRP systems. In order to keep the same ratio of FRP (ρ_{FRP} = 2.6% for glass fibers and 2% for carbon fibers), all specimens were strengthened using U-wrap sheets in one, two and three layers of FRP with respect to the beam's size. The results showed a size effect due to EB-GFRP strengthening system in specimens of the first series; in fact, these specimens exhibited a 9% loss in shear strength by increasing the beam's size from 200 to 600 mm, compared to 14% gain in similar non-strengthened RC beams. However, no size effect was obtained in all pre-cracked specimens, neither in conventional (non-strengthened) RC beams nor in shear-strengthened one with GFRP or CFRP.

RESULTS SYNTHESIS AND RECOMMENDATIONS

The size effect in shear of conventional RC structures is well documented and several studies have evaluated the related major parameters, such as size of aggregates, ratio of longitudinal and transverse steel, concrete compressive strength and span to effective depth ratio. This contrasts with RC beams strengthened in shear with EB-FRP where very few studies have been conducted on the subject. Moreover, these few studies did not consider the influence of the above mentioned parameters on the strengthened beams, but instead they investigated solely the effect of the addition of FRP composites, except for ρ_s assessed by Bousselham and Chaallal [7]. The overall results showed an additional size effect associated with the EB-FRP composites; an increase in shear strength loss occurred in strengthened specimens with increasing "*d*" compared to non-strengthened ones, even if higher levels of shear forces were obtained, except for the study by Deniaud and Cheng [3], where the specimens showed a reduction in the size effect.

An interesting point about the influence of concrete compressive strength (f'_c) on the size effect of RC beams should be highlighted. By analysing the database, we noticed that the highest f'_c used in the specimens shear-strengthened with EB-FRP was less than 50 MPa compared to 100 MPa reached in the studies on size effect of conventional concrete beams. Also, among all the studies on shear strengthening with EB-FRP, none has examined the influence of f'_c on the size effect. However, as already observed, the size effect is much more pronounced at high resistance concrete beams (non-strengthened), and at the same time the increase in f'_c plays a major role in shear resistance gain due to FRP, V_{FRP}, especially when the failure mode is by FRP debonding. Li [38] conducted a series of direct shear bond tests to evaluate the effect of concrete strength on bond behavior of FRP/concrete interface; the results showed an additional gain of 76% in load-carrying capacity when f'_c increased from 27 to 61 MPa, where the specimens failed by CFRP debonding from concrete. This is attributed to the fact that the increase in f'_c provides an increase in concrete tensile stress, hence enhancing the bond at the interface FRP/concrete. In addition, increase in "*d*" results in shear force gain due to FRP by increasing the bonding area, which may thus have a positive impact on the size effect with higher f'_c. In order to understand further this behavior and due to lack of research studies on the subject, more investigations are needed on the size effect of RC beams shear-strengthened with EB-FRP with f'_c as the main study parameter.

Analysis of collected data revealed that the parameters of major influence on shear resistance, which may mitigate or amplify the size effect, converge towards the direct impact of diagonal shear cracks. It has been demonstrated in several studies, for geometrically similar RC beams, that the cracks remain similar with openings proportional to the beam's depth, hence linking the size effect and the cracking mechanism. This indicates that the control of shear cracks may diminish or even eliminate the size effect. As already seen in the study by Collins and Kuchma [24], the distribution of crack control longitudinal reinforcement along the entire beam's depth tends to suppress the size effect. Therefore, a good solution to reproduce this distribution could be the use of bidirectional FRP fibers for strengthening in shear. In fact, the fibers in the longitudinal direction of the axis will provide a significant enhancement in shear performance, which is similar and even better than that of the distribution of internal reinforcing bars because the fibers will intercept and control all the cracks along the entire depth of the section.

For RC beams shear-strengthened with EB-FRP, the authors considered different approaches to keep the same FRP ratio (ρ_{FRP}) with increasing "*d*", which may compromise the integrity of interpretation on size effect due to FRP. In fact, in the study by Bae [6], the increase in the amount of FRP was scaled with the width of FRP strips in one layer, while [3, 7] varied the FRP density while keeping the same number of layers for the same series of specimens. In addition, [4, 5, 8] increased the amount of FRP by increasing the number of layers. However, there are still outstanding issues that need to be investigated, such as: (i) the maximum number of CFRP plies that can be installed without exhibiting slippage or debonding, particularly on vertical surfaces where strengthening in shear is required; (ii) the effectiveness of shear strengthening with multilayer CFRP fabrics compared to one single layer (monolayer) of equivalent density, taking into account the premature debonding failure and the effect of CFRP thickness.

CONCLUSIONS

This paper focuses on the assessment of different parameters of major influence on the size effect in shear of RC beams, either reinforced with steel and FRP bars or shear-strengthened with EB-FRP. An extensive database from literature was developed on the subject with more than 470 test specimens from 48 experimental studies. The following conclusions can be drawn from the analysis and synthesis of the gathered data:

- 76% of available experimental data on size effect are based on specimens with *d* less than 700 mm. Moreover, just 6% of all studies corresponded to RC beams strengthened in shear with EB-FRP, in which 77% consisted of *d* less than 500 mm.
- The size effect in shear of RC beams is influenced by five major parameters: size of aggregates (a_g), concrete compressive strength (f'_c), longitudinal and transverse reinforcement (ρ_w, ρ_{FRP} and ρ_s), as well as

shear span-to-effective depth ratio (*a/d*). The size effect may be suppressed with increasing a_g provided that a good correlation with d is established. It can also be mitigated with the presence of steel stirrups ρ_s and with the distribution of ρ_w along the entire beam's depth. However, it is observed that the size effect is much more pronounced at high resistance concrete beams, as well as in deep beams compared to slender ones.

- The few studies conducted on RC beams shear-strengthened with EB-FRP investigated the behavior of specimens focusing solely on the effect of adding the FRP composites. The results revealed the existence of an additional size effect associated with FRP shear strengthening system using U-wrap configuration, whereas no size effect was observed in full-wrap system.
- None of the parameters of major influence on size effect were assessed by studies on shear strengthening with EB-FRP, except for the transverse steel (ρ_s) considered in only one study, in which the size effect was mitigated as noticed in conventional RC beams. Further research studies are needed to evaluate the influence of all other parameters on the size effect.
- Analysis of data on size effect showed that all parameters of major influence on shear resistance of RC beams converge towards the direct impact of crack openings. This indicates that the control of shear cracks may mitigate and even suppress the size effect.

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APPENDIX A

Table A.1. Experimental database on size effect of RC beams reinforced with steel and FRP bars

RC beams with reinforcing steel bars

Specimen	Geometry of beams				Properties of concrete				Results
	Section	*d* (mm)	*b* (mm)	*a/d*	a_g (mm)	f'_c (MPa)	ρ_w (%)	ρ_s (%)	V_T (kN)
1 - Leonhardt F, Walther R (1962) [1]									
D1/1	rect	70	50	3.0	15	35.8	1.71	0.00	7.4
D2/1	rect	140	100	3.0	15	35.9	1.66	0.00	21.6
D3/1	rect	210	150	3.0	15	37.1	1.62	0.00	47.3
D4/1	rect	280	200	3.0	15	34.0	1.67	0.00	75.6
C1	rect	150	100	3.0	30	37.7	1.33	0.00	22
C2	rect	300	150	3.0	30	37.7	1.33	0.00	66
C3	rect	450	200	3.0	30	37.7	1.33	0.00	104
C4	rect	600	225	3.0	30	37.7	1.33	0.00	155
2 - Kani [1]									
54	rect	136	152	1.0	19.1	26.7	2.76	0.00	158
88	rect	272	152	1.0	19.1	31.4	2.81	0.00	359
69	rect	544	152	1.0	19.1	27.4	2.67	0.00	585
46	rect	136	152	2.0	19.1	25.5	2.76	0.00	69
94	rect	272	152	2.0	19.1	25.3	2.78	0.00	110
61	rect	544	152	2.0	19.1	26.8	2.58	0.00	163
3041	rect	1088	152	2.0	19.1	26.9	2.73	0.00	326
41	rect	136	152	2.5	19.1	27.2	2.6	0.00	51
95	rect	272	152	2.5	19.1	25.3	2.75	0.00	73
65	rect	544	152	2.5	19.1	27.0	2.82	0.00	112
3042	rect	1088	152	2.5	19.1	26.4	2.71	0.00	237
55	rect	136	152	3.0	19.1	25.1	2.89	0.00	33
97	rect	272	152	3.0	19.1	27.2	2.68	0.00	62
71	rect	544	152	3.0	19.1	27.4	2.66	0.00	102
3043	rect	1088	152	3.0	19.1	27.0	2.72	0.00	165
52	rect	136	152	4.0	19.1	24.8	2.69	0.00	29
96	rect	272	152	4.0	19.1	25.3	2.76	0.00	56
63	rect	544	152	4.0	19.1	26.2	2.77	0.00	93
3044	rect	1088	152	4.0	19.1	29.5	2.73	0.00	159
43	rect	136	152	6.0	19.1	28.0	2.73	0.00	29
81	rect	272	152	6.0	19.1	27.5	2.76	0.00	51
66	rect	544	152	6.0	19.1	26.4	2.75	0.00	91
3 - Bhal NS (1968) [1]									
B1	rect	297	240	3.0	-	22.8	1.29	0.00	70
B2	rect	600	240	3.0	-	29.1	1.28	0.00	117
B3	rect	900	240	3.0	-	27.1	1.28	0.00	162
B4	rect	1200	240	3.0	-	24.8	1.28	0.00	177
B5	rect	600	240	3.0	-	26.2	0.64	0.00	104
B7	rect	900	240	3.0	-	26.8	0.64	0.00	135

Specimen	Geometry of beams				Properties of concrete				Results
	Section	*d* (mm)	*b* (mm)	*a/d*	a_g (mm)	f'_c (MPa)	ρ_w (%)	ρ_s (%)	V_T (kN)
4 - Swamy and Shamsuddin [16]									
M3N3/2	T	57	51	1.5	6.35	43.4	0.43	0.00	28
M2N3/2	T	86	76	1.5	9.5	35.9	0.43	0.00	46
M1N3/2	T	171	152	1.5	19	40.0	0.43	0.00	213
M3N3	T	57	51	3.0	6.35	42.1	0.43	0.00	11
M2N3	T	86	76	3.0	9.5	44.5	0.43	0.00	22
M1N3	T	171	152	3.0	19	41.4	0.43	0.00	87
M3N4	T	57	51	4.0	6.35	42.1	0.43	0.00	8
M2N4	T	86	76	4.0	9.5	41.4	0.43	0.00	18
M1N4	T	171	152	4.0	19	43.0	0.43	0.00	66
M3W3/2	T	57	51	1.5	6.35	34.8	0.43	0.61	17
M2W3/2	T	86	76	1.5	9.5	35.7	0.43	0.61	48
M1W3/2	T	171	152	1.5	19	34.5	0.43	0.61	164
M3W3	T	57	51	3.0	6.35	36.2	0.43	0.61	15
M2W3	T	86	76	3.0	9.5	33.2	0.43	0.61	32
M1W3	T	171	152	3.0	19	34.1	0.43	0.61	119
M3W4	T	57	51	4.0	6.35	39.0	0.43	0.61	13
M2W4	T	86	76	4.0	9.5	33.2	0.43	0.61	29
M1W4	T	171	152	4.0	19	37.6	0.43	0.61	118
M3N3C	T	57	51	3.0	6.35	41.0	0.43	0.00	9
M2N3C	T	86	76	3.0	6.35	41.0	0.43	0.00	23
M3N3B	T	57	51	3.0	9.5	43.4	0.43	0.00	13
M2N3B	T	86	76	3.0	9.5	43.4	0.43	0.00	22
M1N3B	T	171	152	3.0	9.5	39.2	0.43	0.00	82
M2N3A	T	86	76	3.0	19	43.0	0.43	0.00	26
M1N3A	T	171	152	3.0	19	43.0	0.43	0.00	79
M1N3D	T	171	152	3.0	38	31.0	0.43	0.00	82
5 - Taylor [17]									
D3	rect	140	60	3.0	2.4	40.0	1.35	0.00	10.6
C6	rect	232	100	3.0	2.4	36.0	1.35	0.00	27.5
C2	rect	232	100	3.0	9	32.0	1.35	0.00	24
B3	rect	465	200	3.0	9	40.0	1.35	0.00	85.3
B2	rect	465	200	3.0	19	31.0	1.35	0.00	87.3
B1	rect	465	200	3.0	38	34.0	1.35	0.00	104
A2	rect	930	400	3.0	19	31.8	1.35	0.00	328
A1	rect	930	400	3.0	38	36.4	1.35	0.00	358
6 - Walraven JC (1978) [1]									
A1	rect	125	200	3.0	-	27.5	0.83	0.00	30
A2	rect	420	200	3.0	-	27.4	0.74	0.00	71

Specimen	Section	d (mm)	b (mm)	a/d	a_g (mm)	f'_c (MPa)	ρ_w (%)	ρ_s (%)	V_T (kN)
A3	rect	720	200	3.0	-	27.8	0.79	0.00	101
7- Chana [18]									
6.1	rect	42	23.5	3.0	2.4	35.8	1.8	0.00	2.14
4.1a	rect	106	60	3.0	5	30.9	1.78	0.00	9.9
3.1a	rect	177	100	3.0	10	34.5	1.7	0.00	23.8
2.1a	rect	356	203	3.0	20	49.3	1.73	0.00	96
8 - Iguro [19]									
1	rect	100	158	1.5	10	20.6	0.4	0.00	13.2
2	rect	200	158	1.5	10	19.7	0.4	0.00	26.6
3	rect	600	300	1.5	10	21.1	0.4	0.00	83.5
4	rect	1000	500	1.5	10	27.2	0.4	0.00	178
5	rect	1000	500	1.5	25	21.9	0.4	0.00	199
6	rect	2000	1000	1.5	25	28.5	0.4	0.00	698
7	rect	3000	1500	1.5	25	24.3	0.4	0.00	1413
9 - Niwa Y *et al.* (1987) [2]									
3	rect	1000	300	3.0	25	23.4	0.14	0.00	102
2	rect	2000	600	3.0	25	24.9	0.14	0.00	382
1	rect	2000	600	3.0	25	25.8	0.28	0.00	402
10 - Bažant and Kazemi [39]									
1	rect	21	38	3.0	4.8	46.2	1.62	0.00	2
2	rect	41	38	3.0	4.8	46.2	1.62	0.00	2.7
3	rect	83	38	3.0	4.8	46.2	1.62	0.00	4.5
4	rect	165	38	3.0	4.8	46.2	1.62	0.00	7.3
5	rect	330	38	3.0	4.8	46.2	1.62	0.00	9.3
11- Walraven and Lehwalter [40]									
A1	rect	125	200	3.0	16	34.2	0.83	0.00	30
A2	rect	420	200	3.0	16	34.2	0.74	0.00	70.6
A3	rect	720	200	3.0	16	34.8	0.79	0.00	101
B1	rect	125	200	3.0	16	37.6	0.83	0.00	40
B2	rect	420	200	3.0	16	37.6	0.74	0.00	60.5
B3	rect	720	200	3.0	16	34.7	0.79	0.00	79.2
V711	rect	160	250	1.0	16	18.1	1.52	0.00	165
V022	rect	360	250	1.0	16	19.9	1.13	0.00	270
V511	rect	560	250	1.0	16	19.8	1.12	0.00	350
V411	rect	740	250	1.0	16	19.4	1.10	0.00	365
V211	rect	930	250	1.0	16	20.0	1.08	0.00	473
V711/4	rect	160	250	1.0	16	19.5	1.50	0.13	207
V711/4	rect	360	250	1.0	16	18.2	1.13	0.13	317
V511/4	rect	560	250	1.0	16	18.7	1.12	0.14	465
V411/4	rect	760	250	1.0	16	17.0	1.07	0.17	467
V711/4	rect	160	250	1.0	16	19.6	1.50	0.35	380

Specimen	Section	d (mm)	b (mm)	a/d	a_g (mm)	f'_c (MPa)	ρ_w (%)	ρ_s (%)	V_T (kN)
V022/3	rect	360	250	1.0	16	19.6	1.13	0.35	380
V511/3	rect	560	250	1.0	16	21.3	1.12	0.33	580
V411/3	rect	760	250	1.0	16	19.8	1.07	0.33	665
12 - Grimm (1997) [2]									
s1.1	rect	153	300	3.7	16	85.6	1.34	0.00	70
s2.2	rect	348	300	3.5	16	86.7	1.88	0.00	187
s3.2	rect	718	300	3.7	16	89.0	1.72	0.00	259
s1.3	rect	146	300	3.9	16	89.0	4.22	0.00	98.6
s2.4	rect	328	300	3.8	16	89.4	3.76	0.00	230
s3.4	rect	690	300	3.8	16	89.4	3.57	0.00	379
13 - Ghannoum [20]									
N90	rect	65	400	2.5	20	34.2	1.2	0.00	42.5
N155	rect	128	400	2.5	20	34.2	1.2	0.00	84.6
N220	rect	190	400	2.5	20	34.2	1.2	0.00	104
N350	rect	313	400	2.5	20	34.2	1.2	0.00	158
N485	rect	440	400	2.5	20	34.2	1.2	0.00	188
N960	rect	869	400	2.5	20	34.2	1.2	0.00	367
N90	rect	65	400	2.5	20	34.2	2	0.00	76
N155	rect	128	400	2.5	20	34.2	2	0.00	112
N220	rect	190	400	2.5	20	34.2	2	0.00	123
N350	rect	313	400	2.5	20	34.2	2	0.00	179
N485	rect	440	400	2.5	20	34.2	2	0.00	215
N960	rect	869	400	2.5	20	34.2	2	0.00	386
H90	rect	65	400	2.5	10	58.6	1.2	0.00	52
H155	rect	128	400	2.5	10	58.6	1.2	0.00	77
H220	rect	190	400	2.5	10	58.6	1.2	0.00	106
H350	rect	313	400	2.5	10	58.6	1.2	0.00	157
H485	rect	440	400	2.5	10	58.6	1.2	0.00	199
H960	rect	869	400	2.5	10	58.6	1.2	0.00	317
H90	rect	65	400	2.5	10	58.6	2	0.00	77.4
H155	rect	128	400	2.5	10	58.6	2	0.00	105
H220	rect	190	400	2.5	10	58.6	2	0.00	135
H350	rect	313	400	2.5	10	58.6	2	0.00	190
H485	rect	440	400	2.5	10	58.6	2	0.00	199
H960	rect	869	400	2.5	10	58.6	2	0.00	337
14 – Podgorniak S (1998) [2]									
BN12	rect	110	300	3.1	10	35.2	0.91	0.00	40
BN25	rect	225	300	3.0	10	35.2	0.89	0.00	73
BN50	rect	450	300	3.0	10	35.2	0.81	0.00	132
BN100	rect	925	300	2.9	10	35.2	0.76	0.00	192
BH50	rect	450	300	3.0	10	94.1	0.81	0.00	132

Specimen	Section	*d* (mm)	*b* (mm)	*a/d*	a_g (mm)	f'_c (MPa)	ρ_w (%)	ρ_s (%)	V_T (kN)
BH100	rect	925	300	2.9	10	94.1	0.76	0.00	193
15 - Collins and Kuchma [24]									
BN12	rect	110	300	3.1	10	37.2	0.91	0.00	40
BN25	rect	225	300	3.0	10	37.2	0.89	0.00	73
BN50	rect	450	300	3.0	10	37.2	0.81	0.00	132
BN100	rect	925	300	2.9	10	37.2	0.76	0.00	192
BND25	rect	225	300	3.0	10	37.2	1.31	0.00	112
BND50	rect	450	300	3.0	10	37.2	1.11	0.00	163
BND100	rect	925	300	2.9	10	37.2	1.05	0.00	258
BH25	rect	225	300	3.0	10	98.8	0.89	0.00	85
BH50	rect	450	300	3.0	10	98.8	0.81	0.00	132
BH100	rect	925	300	2.9	10	98.8	0.76	0.00	193
BHD25	rect	225	300	3.0	10	98.8	1.31	0.00	111
BHD50	rect	450	300	3.0	10	98.8	1.11	0.00	193
BHD100	rect	925	300	2.9	10	98.8	1.05	0.00	278
SE50A-45	rect	459	169	2.7	10	52.5	1.03	0	69
SE100A-45	rect	920	295	2.5	10	50	1.03	0	201
SE50B-45	rect	459	169	2.7	10	52.5	1.16	0	87
SE100B-45	rect	920	295	2.5	10	50	1.36	0	281
SE50A-M-69	rect	459	169	2.7	10	74	1.03	0.653	139
SE100A-M-69	rect	920	295	2.5	10	71	1.03	0.804	516
SE50B-M-69	rect	459	169	2.7	10	74	1.16	0.653	152
SE100B-M-69	rect	920	295	2.5	10	75	1.36	0.804	583
SE50A-83	rect	459	169	2.7	10	91	1.03	0	73
SE100A-83	rect	920	295	2.5	10	86	1.03	0	184
SE50B-83	rect	459	169	2.7	10	91	1.16	0	101
SE100B-83	rect	920	295	2.5	10	86	1.36	0	365
16 - Tan and Lu [31]									
1-500/0.50	rect	444	140	0.6	-	49.1	2.60	0.00	850
2-1000/0.50	rect	884	140	0.6	-	31.2	2.60	0.00	875
3-1400/0.50	rect	1251	140	0.6	-	32.8	2.60	0.00	1175
4-1750/0.50	rect	1559	140	0.6	-	42.6	2.60	0.00	1636
1-500/0.75	rect	444	140	0.8	-	42.5	2.60	0.00	700
2-1000/0.75	rect	884	140	0.8	-	32.7	2.60	0.00	650
3-1400/0.75	rect	1251	140	0.8	-	36.2	2.60	0.00	950
4-1750/0.75	rect	1559	140	0.8	-	40.4	2.60	0.00	1240
1-500/1.00	rect	444	140	1.1	-	37.4	2.60	0.00	570
2-1000/1.00	rect	884	140	1.1	-	30.8	2.60	0.00	435
3-1400/1.00	rect	1251	140	1.1	-	35.3	2.60	0.00	800
4-1750/1.00	rect	1559	140	1.1	-	44.8	2.60	0.00	1000

Specimen	Section	*d* (mm)	*b* (mm)	*a/d*	a_g (mm)	f'_c (MPa)	ρ_w (%)	ρ_s (%)	V_T (kN)
17 - Kotsovos and Pavlovic [32]									
D1	rect	70	50	3.0	-	38.0	1.62	0.00	7
D2	rect	140	100	3.0	-	38.2	1.62	0.00	22
D3	rect	210	150	3.0	-	39.5	1.62	0.00	45
D4	rect	280	200	3.0	-	36.1	1.62	0.00	74
C1	rect	150	100	3.0	-	40.0	1.34	0.00	22
C2	rect	300	150	3.0	-	40.0	1.34	0.00	66
C3	rect	450	200	3.0	-	40.0	1.34	0.00	101
C4	rect	600	225	3.0	-	40.0	1.34	0.00	155
D1s	rect	70	50	3.0	-	38.0	1.62	0.25	8
D2s	rect	140	100	3.0	-	38.2	1.62	0.25	29
D3s	rect	210	150	3.0	-	39.5	1.62	0.25	63
D4s	rect	280	200	3.0	-	36.1	1.62	0.25	117
C1s	rect	150	100	3.0	-	40.0	1.34	0.17	32
C2s	rect	300	150	3.0	-	40.0	1.34	0.17	84
C3s	rect	450	200	3.0	-	40.0	1.34	0.17	192
C4s	rect	600	225	3	-	40	1.34	0.17	270
18 - Fujita [29]									
L-25-3	rect	250	150	3.0	20	36.4	1.53	0.00	56
L-50-3	rect	500	150	3.0	20	36.4	1.53	0.00	79
L-100-3	rect	1000	350	3.0	20	35.7	1.36	0.00	319
M-25-3	rect	250	150	3.0	20	51.9	1.53	0.00	65
M-50-3	rect	500	150	3.0	20	51.9	1.53	0.00	113
M-100-3	rect	1000	350	3.0	20	53.0	1.36	0.00	340
U-25-3	rect	250	150	3.0	20	92.9	1.53	0.00	47
U-50-3	rect	500	150	3.0	20	102.0	1.53	0.00	86
U-100-3	rect	1000	350	3.0	20	103.0	1.36	0.00	280
19 - Yang [41]									
L5-40	rect	355	160	0.6	19	31.4	1	0.00	447
L5-60	rect	555	160	0.5	19	31.4	0.98	0.00	535
L5-75	rect	685	160	0.6	19	31.4	1	0.00	597
L5-100	rect	935	160	0.5	19	31.4	0.9	0.00	582
L10-40	rect	355	160	1.1	19	31.4	1	0.00	312
L10-60	rect	555	160	1.1	19	31.4	0.98	0.00	375
L10-75	rect	685	160	1.1	19	31.4	1	0.00	330
L10-100	rect	935	160	1.1	19	31.4	0.9	0.00	544
UH5-40	rect	355	160	0.6	19	78.5	1	0.00	733
UH5-60	rect	555	160	0.5	19	78.5	0.98	0.00	823
UH5-75	rect	685	160	0.6	19	78.5	1	0.00	1010
UH5-100	rect	935	160	0.5	19	78.5	0.9	0.00	1029

Specimen	Section	*d* (mm)	*b* (mm)	*a/d*	a_g (mm)	f'_c (MPa)	ρ_w (%)	ρ_s (%)	V_T (kN)
UH10-40	rect	355	160	1.1	19	78.5	1	0.00	499
UH10-60	rect	555	160	1.1	19	78.5	0.98	0.00	573
UH10-75	rect	685	160	1.1	19	78.5	1	0.00	361
UH10-100	rect	935	160	1.1	19	78.5	0.9	0.00	769
20 - Bentz and Buckley [42]									
SBB1.1	rect	84	104	2.9	10	35.6	1.63	0.00	14
SBB2.1	rect	168	106	2.9	10	34.3	1.59	0.00	29
SBB3.1	rect	333	105	3.0	10	36.1	1.55	0.00	42
SBB1.2	rect	84	105	2.9	10	35.6	1.61	0.00	19
SBB2.2	rect	168	105	2.9	10	34.3	1.61	0.00	30
SBB3.2	rect	333	101	3.0	10	36.1	1.61	0.00	41
SBB1.3	rect	84	104	2.9	10	35.6	1.63	0.00	15
SBB2.3	rect	166	106	3.0	10	34.3	1.61	0.00	30
SBB3.3	rect	333	101	3.0	10	36.1	1.61	0.00	43
21 - Zhang and Tan [44]									
1DB35bw	rect	313	80	1.1	10	25.9	1.25	0.40	100
1DB50bw	rect	454	115	1.1	10	27.4	1.28	0.39	187
1DB70bw	rect	642	160	1.1	10	28.3	1.22	0.45	427
1DB100bw	rect	904	230	1.1	10	28.7	1.2	0.41	775
2DB35	rect	314	80	1.1	10	27.4	1.25	0.00	85
2DB50	rect	459	80	1.1	10	32.4	1.15	0.00	136
2DB70	rect	650	80	1.1	10	24.8	1.28	0.00	156
2DB100	rect	926	80	1.1	10	30.6	1.26	0.00	242
3DB35b	rect	314	80	1.1	10	27.4	1.25	0.00	85
3DB50b	rect	454	115	1.1	10	28.3	1.28	0.00	167
3DB70b	rect	642	160	1.1	10	28.7	1.22	0.00	361
3DB100b	rect	904	230	1.1	10	29.3	1.2	0.00	672
22 - Yang and Ashour [47]									
L5-40	rect	355	160	0.6	25	32.4	1	0.00	405
L5-60	rect	555	160	0.5	25	32.4	0.97	0.00	456
L5-72	rect	653	160	0.6	25	32.4	1.1	0.00	492
L10-40	rect	355	160	1.1	25	32.1	1	0.00	201
L10-60	rect	555	160	1.1	25	32.1	0.97	0.00	262
L10-72	rect	653	160	1.1	25	32.1	1.1	0.00	300
H6-40	rect	355	160	0.7	25	65.1	1	0.00	590
H6-60	rect	555	160	0.6	25	65.1	0.97	0.00	634
H6-72	rect	653	160	0.7	25	65.1	1.1	0.00	698
H10-40	rect	355	160	1.1	25	67.5	1	0.00	335
H10-60	rect	555	160	1.1	25	68.2	0.97	0.00	372
H10-72	rect	653	160	1.1	25	67.5	1.1	0.00	392
23 - Zakaria [25]									
A1 left	rect	160	200	2.0	25	40.0	2.86	0.72	171
A2 left	rect	280	200	2.0	25	40.0	2.83	0.72	282
A3 left	rect	432	200	2.0	25	40.0	2.84	0.72	432
A4 left	rect	669	200	2.0	25	40.0	2.84	0.72	718
24 - Sneed and Ramirez [43]									
1-1	rect	232	305	3.0	9.5	66.1	1.2	0.00	131
1-2	rect	530	306	3.0	9.5	66.1	1.25	0.00	140
1-3	rect	681	305	3.0	9.5	65.0	1.24	0.00	148
1-4	rect	822	306	3.0	9.5	74.8	1.3	0.00	168
2-1	rect	233	203	3.0	9.5	68.6	1.26	0.00	57
2-2	rect	529	408	3.0	9.5	64.8	1.2	0.00	156
2-3	rect	684	508	3.0	9.5	68.1	1.3	0.00	262
2-4	rect	822	613	3.0	9.5	72.9	1.3	0.00	353
25 - Yu [45]									
B5N	rect	426	250	2.6	19	49.6	1.15	0.00	172
B6N	rect	524	298	2.6	19	49.6	1.18	0.00	196
B8N	rect	690	299	2.7	19	43.7	1.19	0.00	241
B10N	rect	902	310	2.5	19	54.2	1.1	0.00	323
B12N	rect	1098	605	2.5	19	54.2	1.11	0.00	694
B10L	rect	896	308	2.5	19	54.2	0.67	0.00	201
26 - Kim [46]									
NA-S2	rect	300	200	2.5	25	31.8	1.9	0.00	76
NA-M2	rect	450	200	2.5	25	31.8	1.9	0.00	107
NA-L2	rect	600	200	2.5	25	31.8	1.9	0.00	126
NA-M3	rect	450	300	2.5	25	31.8	1.9	0.00	157
NA-L4	rect	600	400	2.5	25	31.8	1.9	0.00	256
RH-S2	rect	300	200	2.5	25	32.6	1.9	0.00	61
RH-M2	rect	450	200	2.5	25	32.6	1.9	0.00	109
RH-L2	rect	600	200	2.5	25	32.6	1.9	0.00	126
RH-M3	rect	450	300	2.5	25	32.6	1.9	0.00	154
RH-L4	rect	600	400	2.5	25	32.6	1.9	0.00	262
RF-S2	rect	300	200	2.5	25	34.9	1.9	0.00	73
RF-M2	rect	450	200	2.5	25	34.9	1.9	0.00	96
RF-L2	rect	600	200	2.5	25	34.9	1.9	0.00	125
RF-M3	rect	450	300	2.5	25	34.9	1.9	0.00	160
RF-L4	rect	600	400	2.5	25	34.9	1.9	0.00	257
27 - Yu [48]									
B5N	rect	426	250	2.6	-	39.2	1.15	0.00	154
B6N	rect	524	298	2.6	-	39.2	1.18	0.00	180

Specimen	Section	d mm	b mm	a/d	a_g mm	f'_c MPa	ρ_w (%)	ρ_s (%)	V_T (kN)
B8N	rect	690	299	2.7	-	34.5	1.19	0.00	235
B10N	rect	902	310	2.5	-	42.8	1.1	0.00	299
B12N	rect	1098	605	2.5	-	42.8	1.11	0.00	571
B10L	rect	896	308	2.5	-	42.8	0.67	0.00	171
28 - Arun and Ramakrishnan [49]									
MNR1	rect	400	150	2.6	-	48.8	2.78	0.34	269
MNR2	rect	450	150	2.6	-	48.8	2.78	0.30	255
MNR3	rect	500	150	2.6	-	48.8	2.78	0.27	193
NNR1	rect	400	150	2.6	-	37.6	3.43	0.34	265
NNR2	rect	450	150	2.6	-	37.6	3.43	0.30	234
NNR3	rect	500	150	2.6	-	48.8	3.43	0.27	193
ONR1	rect	400	150	2.6	-	37.6	2.78	0.37	269
ONR2	rect	450	150	2.6	-	37.6	2.78	0.34	250
ONR3	rect	500	150	2.6	-	37.6	2.78	0.30	208
29 - Syroka-Korol and Tejchman [50]									
SL20	rect	160	200	3.0	16	-	1	0.00	46
SL40	rect	360	200	3.0	16	-	1	0.00	86
SL80	rect	750	200	3.0	16	-	1	0.00	132
SH22	rect	180	200	1.0	16	-	0.63	0.00	170
SH40	rect	360	200	1.0	16	-	0.63	0.00	215
SH78	rect	720	200	1.0	16	-	0.63	0.00	257
30 - Birrcher [51]									
IV-2123-1.2-02	rect	495	533	1.2	19	31.9	2.3	0.17	2631
III-1.2-02	rect	980	533	1.2	19	28.2	2.3	0.19	3760
IV-2175-1.2-02	rect	1750	533	1.2	19	34.5	2.3	0.21	5436
IV-2123-1.85-03	rect	495	533	1.9	19	28.7	2.3	0.30	1462
III-1.85-02b	rect	980	533	1.8	19	22.7	2.3	0.19	2083
IV-2175-1.85-02	rect	1750	533	1.9	19	34.0	2.3	0.19	3391
IV-2123-2.5-02	rect	495	533	2.5	19	31.5	2.3	0.17	716
III-2.5-02	rect	980	533	2.5	19	31.9	2.3	0.19	1324
IV-2175-2.5-02	rect	1750	533	2.5	19	34.5	2.3	0.21	2270
31 - El-Sayed and Shuraim [28]									
B350-1-30	rect	293	150	1.0	20	26.1	1.4	0.00	204
B500-1-30	rect	419	150	1.0	20	26.1	1.47	0.00	235
B700-1-30	rect	615	150	1.0	20	26.1	1.44	0.00	453
B1000-1-30	rect	910	150	1.0	20	26.1	1.47	0.00	546
B350-1-55	rect	293	150	1.0	20	53.9	1.4	0.00	380
B500-1-55	rect	419	150	1.0	20	53.9	1.47	0.00	416
B700-1-55	rect	615	150	1.0	20	53.9	1.44	0.00	590
B1000-1-55	rect	910	150	1.0	20	53.9	1.47	0.00	743
B350-1-75	rect	293	150	1.0	20	70.1	1.4	0.00	390
B500-1-75	rect	419	150	1.0	20	70.1	1.47	0.00	441
B700-1-75	rect	615	150	1.0	20	70.1	1.44	0.00	771
B1000-1-75	rect	910	150	1.0	20	70.1	1.47	0.00	810
32 - Minelli [35]									
PC-50	rect	455	200	2.5	20	25.7	1.04	0.00	111
PC-100	rect	910	200	2.5	20	25.7	1.03	0.00	195
PC-100	rect	910	200	2.5	20	55.0	1.03	0.00	207
MSR-50 1	rect	455	200	2.5	20	25.7	1.04	0.08	176
MSR-100	rect	910	200	2.5	20	25.7	1.03	0.04	329
MSR-100	rect	910	200	2.5	20	55.0	1.03	0.04	451
FRC-50 1	rect	455	200	2.5	20	25.7	1.04	SFRC 20kg/m3	197
FRC-100	rect	910	200	2.5	20	25.7	1.03	SFRC 20kg/m3	258
FRC-100	rect	910	200	2.5	20	55.0	1.03	SFRC 20kg/m3	339
33 - Minelli [34]									
H500 PC	rect	440	250	3.0	16	38.7	1.12	0.00	116
H1000PC	rect	940	250	3.0	16	32.1	1.07	0.00	188
H1500 PC	rect	1440	250	3.0	16	33.1	1.01	0.00	211
H500 FRC50	rect	440	250	3.0	16	38.7	1.12	SFRC 50kg/m3	240
H1000 FRC50	rect	940	250	3.0	16	32.1	1.07	SFRC 50kg/m3	272
H1500 FRC50	rect	1440	250	3.0	16	33.1	1.01	SFRC 50kg/m3	484
H500 FRC75	rect	440	250	3.0	16	38.7	1.12	SFRC 75kg/m3	235
H1000 FRC 75	rect	940	250	3.0	16	32.1	1.07	SFRC 75kg/m3	351
H1500 FRC 75	rect	1440	250	3.0	16	33.1	1.01	SFRC 75kg/m3	554
34 - Shoaib [36]									
N31	rect	258	310	3.0	10	23.0	2.5	1.00	211
N61	rect	531	300	3.0	10	23.0	1.88	1.00	252
N10-1	rect	923	300	3.0	10	41.0	1.44	1.00	492
N32	rect	240	310	3.0	10	41.0	4.03	1.00	281
N62	rect	523	300	3.0	10	23.0	2.55	1.00	242
N10-2	rect	920	300	3.0	10	41.0	2.03	1.00	497
H31	rect	258	310	3.0	10	41.0	2.5	1.00	278
H61	rect	531	300	3.0	10	41.0	1.88	1.00	423
H10-1	rect	923	300	3.0	10	80.0	1.44	1.00	646
H32	rect	240	310	3.0	10	80.0	4.03	1.00	458
H62	rect	523	300	3.0	10	41.0	2.55	1.00	444
H10-2	rect	920	300	3.0	10	80.0	2.03	1.00	644

RC beams with reinforcing FRP bars

Specimen	Geometry of beams				Properties of concrete				Results
	Section	*d* (mm)	*b* (mm)	*a/d*	a_g (mm)	f'_c (MPa)	ρ_{FRP} (%)	ρ_s (%)	V_T (kN)
35 - Massam L (2001) [3]									
LB/2/0.5/0	rect	194	450	3.9	10	35	0.12	0.00	54
LB/4/0.5/0	rect	438	450	3.5	10	35	0.10	0.00	87
LB/2/0.5/0	rect	938	450	3.2	10	46	0.09	0.00	135
LB/2/2/0	rect	188	450	4.1	10	35	0.47	0.00	74
LB/4/2/0	rect	504	450	3.8	10	35	0.44	0.00	138
LB/8/2/0	rect	860	450	3.6	10	36	0.41	0.00	231
36 - Matta [53]									
I-1	rect	883	457	3.1.	-	38.8	0.59	0.22	123
II-1	rect	883	914	3.1	-	29	0.59	0.58	288
I-2	rect	883	457	3.1	-	35.4	0.59	0.58	171
II-2	rect	880	914	3.1	-	31.5	0.89	0.58	431
37 - Bentz [26]									
S05-0	rect	194	450	3.9	10	35	0.66	0.00	55
M05-0	rect	438	450	3.5	10	35	0.55	0.00	86
L05-0	rect	937	450	3.3	10	46	0.51	0.00	135
L05-1	rect	937	450	3.3	10	46	0.51	0.71	237
L05-2	rect	937	450	3.3	10	49	0.51	1.42	246
S20-0	rect	188	450	4.1	10	35	2.54	0.00	74
M20-0	rect	405	450	3.8	10	35	2.36	0.00	138
L20-0	rect	857	450	3.6	10	36	2.23	0.00	232
M20-1	rect	405	450	3.8	10	35	2.36	0.71	154
L20-1	rect	857	450	3.6	10	36	2.23	0.71	500
L20-2	rect	857	450	3.6	10	42	2.23	1.42	690
38 - Alam and Hussein [27]									
G-350-70	rect	291	250	2.5	20	65.3	0.87	0.00	76
G-500-70	rect	442	250	2.5	20	74.2	1.25	0.00	116
G-650-70	rect	578	300	2.5	20	74.2	1.37	0.00	155
C-350-70	rect	310	250	2.5	20	65.3	0.42	0.00	72
C-500-70	rect	449	250	2.5	20	74.2	0.69	0.00	100
C-650-70	rect	594	300	2.5	20	74.2	0.65	0.00	146
39 - Matta [14]									
S3-0.12-2A	rect	292	114	3.1	19	32.1	0.13	0.00	18
S1-0.12-2B	rect	883	457	3.1	19	29.6	0.12	0.00	151
S3-0.24-2B	rect	292	114	3.1	19	40.6	0.28	0.00	21
S1-0.24-2B	rect	880	457	3.1	19	30.7	0.24	0.00	213
40 - Alam and Hussein [52]									
S-350	rect	310	250	2.5	20	37.4	0.90	0.00	84
S-500	rect	458	250	2.5	20	42.4	0.87	0.00	111
S-650	rect	608	300	2.5	20	49.3	0.88	0.00	156
S-800	rect	758	300	2.4	20	41.8	0.88	0.00	200
C-350	rect	310	250	2.5	20	44.7	0.42	0.00	65
C-500	rect	460	250	2.5	20	34.5	0.45	0.00	74
C-650	rect	594	300	2.5	20	42.4	0.43	0.00	113
C-800	rect	744	300	2.4	20	41.8	0.40	0.00	139
G-350	rect	305	250	2.5	20	39.8	0.86	0.00	61
G-500	rect	440	250	2.5	20	37.4	0.90	0.00	77
G-650	rect	584	300	2.5	20	37	0.91	0.00	104
G-800	rect	734	300	2.4	20	41.8	0.90	0.00	129
41 - Ashour and Kara [54]									
B-200-2	rect	176	200	5.9	-	29	0.25	0.00	18
B-300-2	rect	276	200	3.6	-	35	0.16	0.00	33
B-400-2	rect	376	200	2.7	-	27	0.12	0.00	33
B-200-4	rect	176	200	5.9	-	29	0.50	0.00	21
B-300-4	rect	276	200	3.6	-	35	0.32	0.00	33
B-400-4	rect	376	200	2.7	-	27	0.24	0.00	36
42 - Mahmoud and El-Salakawy [55]									
GN-0.8-S	rect	250	200	3	19	39	0.79	0.00	36
GN-0.8-M	rect	500	200	3	19	39	0.79	0.00	64
GN-0.8-L	rect	750	200	3	19	39	0.76	0.00	93
GN-1.2-S	rect	250	200	3	19	39	1.18	0.00	52
GN-1.2-M	rect	500	200	3	19	44	1.18	0.00	91
GN-1.2-L	rect	750	200	3	19	39	1.14	0.00	99
GH-0.8-S	rect	250	200	3	19	72	0.79	0.00	43
GH-0.8-M	rect	500	200	3	19	70	0.79	0.00	56
GH-0.8-L	rect	750	200	3	19	77	0.76	0.00	74
GH-1.2-S	rect	250	200	3	19	72	1.18	0.00	50
GH-1.2-M	rect	500	200	3	19	70	1.18	0.00	87
GH-1.2-L	rect	750	200	3	19	71	1.14	0.00	101

Note : The number of specimens shown in the table represents tests that are deemed valid. unambiguous and non-repetitive. selected solely for an accurate comparison for the size effect; Results are taken from the study by: [1]Zararis and Papadakis [12], [2]Reineck and Kuchma [13], [3]Matta [14]; The study by Godat, Qu [15] is a numerical modelling of the specimens tested by Qu, Lu [4]

Table A.2 Experimental database on size effect of RC beams shear-strengthened with EB-FRP

RC beams shear-strengthened with EB-FRP														
Specimen	**Geometry of beam**				**Properties of concrete**				**Properties of FRP**				**Exp Result (KN)**	
	Section	***d* (mm)**	***b* (mm)**	***a/d***	**a_g (mm)**	**f'_c (MPa)**	**ρ_w (%)**	**ρ_s (%)**	**Fiber**	**Configuration**	**Layer**	**ρ_{FRP} (%)**	**V_{FRP}**	**V_T**
43 - Deniaud and Cheng [3]														
T4NS	T	330	140	3	-	29	2.30	0.00	-	- -	-	-	-	115
T6NS	T	530	140	2.8	-	44	2.70	0.00	-	- -	-	-	-	110
T4S4	T	330	140	3	-	29	2.30	0.10	-	- -	-	-	-	157
T6S4	T	530	140	2.8	-	44	2.70	0.10	-	- -	-	-	-	188
T4S4-G90	T	330	140	3	-	29	2.30	0.10	G	Cont en U	1	2.60	49	206
T6S4-G90	T	530	140	2.8	-	44	2.70	0.10	G	Cont en U	1	2.60	110	297
44 - Qu [4]														
RC1	Rect	166	100	2	30	51.2	4.10	0.00	-	- -	-	-	-	80
RC2	Rect	330	200	2	30	49.7	4.50	0.00	-	- -	-	-	-	355
RC3	Rect	498	300	2	30	50.5	4.20	0.00	-	- -	-	-	-	813
U4	Rect	166	100	2	30	51.2	4.10	0.00	C	strips en U	1	0.13	22	101
U5	Rect	330	200	2	30	51.2	4.50	0.00	C	strips en U	2	0.13	50	405
U6	Rect	498	300	2	30	51	4.20	0.00	C	strips en U	3	0.13	196	1009
45 - Leung [5]														
SB-C	Rect	155	75	2.5	-	27.4	5.40	0.28	-	- -	-	-	-	41
MB-C	Rect	305	150	2.5	-	27.4	4.40	0.28	-	- -	-	-	-	150
LB-C	Rect	660	300	2.5	-	27.4	4.10	0.28	-	- -	-	-	-	538
SB-U1	Rect	155	75	2.5	-	27.4	5.40	0.28	C	strips en U	1	0.10	24	65
MB-U1	Rect	305	150	2.5	-	27.4	4.40	0.28	C	strips en U	2	0.10	5	155
LB-U2	Rect	660	300	2.5	-	27.4	4.10	0.28	C	strips en U	4	0.10	22	560
SB-F1	Rect	155	75	2.5	-	27.4	5.40	0.28	C	strips W	1	0.10	25	66
MB-F1	Rect	305	150	2.5	-	27.4	4.40	0.28	C	strips W	2	0.10	87	236
LB-F1	Rect	660	300	2.5	-	27.4	4.10	0.28	C	strips W	4	0.10	334	872
46 - Bae [6]														
S-Cont	Rect	305	203	3	-	25.2	0.16	0.00	-	- -	-	-	-	66
M-Cont	Rect	457	305	3	-	32	0.16	0.00	-	- -	-	-	-	159
L-Cont	Rect	610	406	3	-	32	0.18	0.00	-	- -	-	-	-	244
S-Str	Rect	305	203	3	-	25.2	0.16	0.00	C	strips en U	1	0.05	47	113
M-Str	Rect	457	305	3	-	32	0.16	0.00	C	strips en U	1	0.05	87	246
L-Str	Rect	610	406	3	-	32	0.18	0.00	C	strips en U	1	0.05	127	371
47 - Bousselham and Chaallal [7]														
ED2 S0-0L	T	175	95	3	14	25	3.61	0.00	-	- -	-	-	-	36
ED1 S0-0L	T	350	152	3	14	25	3.76	0.00	-	- -	-	-	-	81
ED2 S1-0L	T	175	95	3	14	25	3.61	0.38	-	- -	-	-	-	93
ED1 S1-0L	T	350	152	3	14	25	3.76	0.38	-	- -	-	-	-	263
ED2 S0-1L	T	175	95	3	14	25	3.61	0.00	C	Cont en U	1	0.14	23	59
ED1 S0-1L	T	350	152	3	14	25	3.76	0.00	C	Cont en U	1	0.14	39	120
ED2 S1-1L	T	175	95	3	14	25	3.61	0.38	C	Cont en U	1	0.14	3	96
ED1 S1-1L	T	350	152	3	14	25	3.76	0.38	C	Cont en U	1	0.14	0	255
ED2 S0-2L	T	175	95	3	14	25	3.61	0.00	C	Cont en U	2	0.28	32	69
ED1 S0-2L	T	350	152	3	14	25	3.76	0.00	C	Cont en U	2	0.28	40	122
ED2 S1-2L	T	175	95	3	14	25	3.61	0.38	C	Cont en U	2	0.28	12	105
ED1 S1-2L	T	350	152	3	14	25	3.76	0.38	C	Cont en U	2	0.28	4	267
48 - Nguyen-Minh and Rovňák [8]														
G1-RC1	Rect	175	100	1.7	22	25	1.80	0.19	-	- -	-	-	-	39
G1-RC2	Rect	350	200	1.7	22	25	1.80	0.19	-	- -	-	-	-	170
G1-RC3	Rect	525	300	1.7	22	25	1.80	0.19	-	- -	-	-	-	395
G1-GFRP-1B	Rect	175	100	1.7	22	25	1.80	0.19	G	Cont en U	1	2.60	18	56
G1-GFRP-2A	Rect	350	200	1.7	22	25	1.80	0.19	G	Cont en U	2	2.60	55	225
G1-GFRP-3A	Rect	525	300	1.7	22	25	1.80	0.19	G	Cont en U	3	2.60	64	459
G2-RC1	Rect	196	100	2	22	23.5	2.40	0.16	-	- -	-	-	-	45
G2-RC2	Rect	442	200	2	22	23.5	2.40	0.16	-	- -	-	-	-	225
G2-RC3	Rect	682	300	2	22	23.5	2.40	0.16	-	- -	-	-	-	470
G2-GFRP-1A	Rect	196	100	2	22	23.5	2.40	0.16	G	Cont en U	1	2.60	18	63
G2-GFRP-2A	Rect	442	200	2	22	23.5	2.40	0.16	G	Cont en U	2	2.60	80	305
G2-GFRP-3A	Rect	682	300	2	22	23.5	2.40	0.16	G	Cont en U	3	2.60	180	650
G2-CFRP-1	Rect	196	100	2	22	23.5	2.40	0.16	C	Cont en U	1	2.00	25	70
G2-CFRP-2	Rect	442	200	2	22	23.5	2.40	0.16	C	Cont en U	2	2.00	120	345
G2-CFRP-3	Rect	682	300	2	22	23.5	2.40	0.16	C	Cont en U	3	2.00	260	730

Note: G=glass. C=carbon. Cont=continuous. W=wrapped around