Hindawi Publishing Corporation
Journal of Engineering
Volume 2013, Article ID 912983, 12 pages
http://dx.doi.org/10.1155/2013/912983

Research Article

Application of a Reinforced Self-Compacting Concrete Jacket in Damaged Reinforced Concrete Beams under Monotonic and Repeated Loading

Constantin E. Chalioris, Constantin P. Papadopoulos, Constantin N. Pourzitidis, Dimitrios Fotis, and Kosmas K. Sideris

Department of Civil Engineering, Democritus University of Thrace, 67100 Xanthi, Greece

Correspondence should be addressed to Constantin E. Chalioris; chaliori@civil.duth.gr

Received 27 August 2012; Revised 2 December 2012; Accepted 2 December 2012

Academic Editor: İlker B. Topçu

This paper presents the findings of an experimental study on the application of a reinforced self-compacting concrete jacketing technique in damaged reinforced concrete beams. Test results of 12 specimens subjected to monotonic loading up to failure or under repeated loading steps prior to total failure are included. First, 6 beams were designed to be shear dominated, constructed by commonly used concrete, were initially tested, damaged, and failed in a brittle manner. Afterwards, the shear-damaged beams were retrofitted using a self-compacting concrete U-formed jacket that consisted of small diameter steel bars and U-formed stirrups in order to increase their shear resistance and potentially to alter their initially observed shear response to a more ductile one. The jacketed beams were retested under the same loading. Test results indicated that the application of reinforced self-compacting concrete jacketing in damaged reinforced concrete beams is a promising rehabilitation technique. All the jacketed beams showed enhanced overall structural response and 35% to 50% increased load bearing capacities. The ultimate shear load of the jacketed beams varied from 39.7 to 42.0 kN, whereas the capacity of the original beams was approximately 30% lower. Further, all the retrofitted specimens exhibited typical flexural response with high values of deflection ductility.

1. Introduction

Self-compacting concrete (SCC) consists one of the very latest developments in concrete technology. It was contrived in Japan (1986–88) and even since it marks a milestone in building industry and concrete research. SCC has excellent deformability, high fluidity, and better durability potential and perhaps it is the best example of a rheologically controlled mix. It can flow homogenously under self-weight through and around the most congested reinforcement without segregating or entrapping air [1–4].

The advanced properties of SCC make its applications to spread worldwide. The "self-compactability" characteristics of such cementitious mixtures (concrete and mortars) allow their use with short steel fibres or scrap rubber particles. Further, they ensure a good bond to the embedded reinforcement, such as conventional steel bars and stirrups or fibre-reinforced-polymers (FRP) or textile-reinforced-mortars (TRM) [5–7].

Remarkable workability, filling and passing ability make SCC an optimal material to restore damaged concrete elements. Recently, it has been used in jacketing applications for the repair or/and strengthening of existing or damaged reinforced concrete (RC) members [8–12]. However, the conducted experimental research on the use of SCC jackets with steel reinforcement as a rehabilitation technique is quite limited, has mainly been carried out by the authors of this study, and has preliminary and exploratory character so far.

Jacketing is one of the most favourable and well-known strengthening methods of poor detailed or deficient RC members and structures. It has long been recognized that RC jackets do provide increased strength, stiffness, and overall enhancement of the structural performance [16]. Jackets constructed by conventional cast-in-place concrete

[13–15], premixed, nonshrink, flowable, rapid and high-strength cement-based mortar [17], shotcrete [18], and FRP sheets [15, 19, 20] have been examined as rehabilitation methods in existing inadequate or damaged RC columns, beams, and beam-column joints.

In this paper, the effectiveness of a reinforced self-compacting concrete (RSCC) jacket for the rehabilitation of damaged RC beams is experimentally investigated. For the needs of this study 6 original RC beams were designed to be shear dominated, constructed by commonly used concrete, and initially subjected to monotonic or repeated loading and exhibited severe diagonal cracking and shear failure mode. These damaged specimens were retrofitted using RSCC jackets with small diameter steel reinforcement and the jacketed beams were retested under the same loading conditions. The applied RSCC jacketing was designed in order to provide increased shear resistance to the shear-damaged and stirrup insufficient original beams. The experimental behaviour of the beams and the ability of the used RSCC jacketing technique to ameliorate the capacity of the tested specimens and to change the brittle shear failure mode of the original beams to a more ductile one for the jacketed beams are also discussed.

The published work on the use of SCC jacketing in damaged RC members is extremely limited and therefore this area is still an open field of study. The present paper contributes to the existing literature of SCC applications with tests of retrofitted RC beams with RSCC jackets under monotonic and repeated loading. It should also be mentioned that the behaviour of SCC jacketed beams under repeated loading has not been examined yet.

2. Experimental Program

The experimental program of this study includes tests of 12 specimens adopting the four-point bending scheme shown in Figure 1. Six original RC shear-dominated beams were firstly constructed, tested under monotonic or repeated loading, and damaged. After their rehabilitation using an RSCC jacketing the retrofitted beams were retested under the same loading conditions. Supplementary compression and splitting tests of the commonly used concrete of the original beams and the SCC of the jackets are also included.

2.1. Original Beams. All the original beams had the same total length (1.6 m), the same rectangular cross-sectional dimensions (b_o/h_o = 125/200 mm), and the same effective depth (d_o = 175 mm). Longitudinal steel reinforcement comprised of deformed bars with diameter ∅8, 2 or 4 ∅8 compression bars at the top and 4∅8 tension bars at the bottom of the beams' cross-section. Mild steel closed stirrups with diameter ∅5 distributed at a uniform spacing of 300, 200 and 150 mm were also provided.

The original beams were designed to be shear dominated in the insufficiency of stirrups. The choice of the cross-sectional dimensions and the reinforcements of these beams was primarily dictated by the availability of formwork and laboratory testing capacities, resulting in a specimen of approximately one-half scale of a typical beam of an existing RC structure (e.g., realistic shear-dominated beams could have width 250 mm, height 400 mm, length 3.2 m, 2∅12 up, and 3∅14 bottom as longitudinal steel reinforcement and ∅8 diameter of closed steel stirrups).

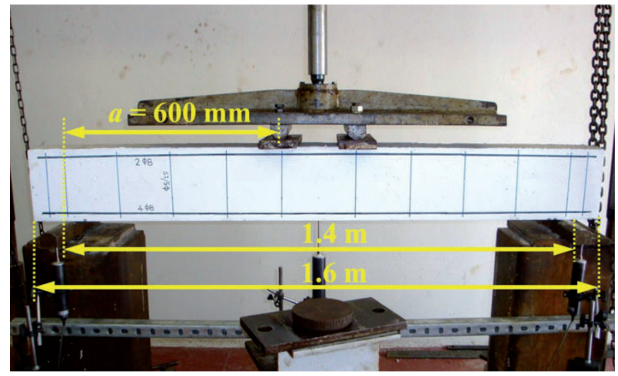


FIGURE 1: Test setup.

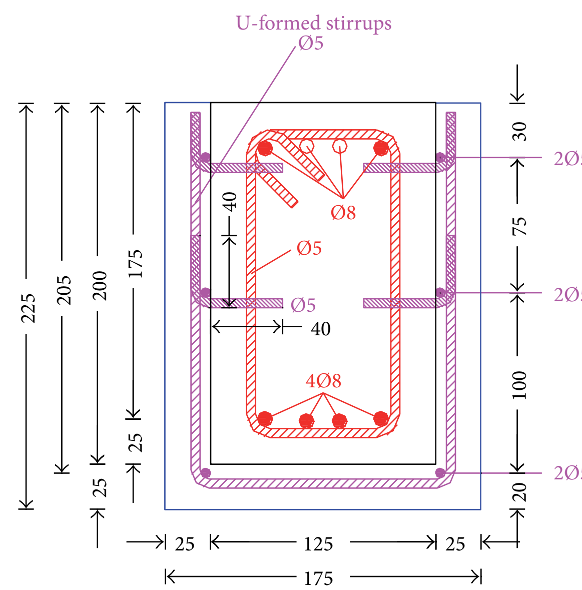


FIGURE 2: Cross-sectional dimensions and steel reinforcement of the jacketed beams.

Reinforcement arrangement of the specimens is shown in Figure 2 and summarized in Table 1. Monotonic and repeated loading is denoted as "M" and "R", respectively, in the codified names of the beams in Table 1. Thus, original beams M1, M2, and M3 were tested under monotonic loading up to failure and original beams R1, R2, and R3 were subjected to repeated loading steps prior to failure.

The measured tensile yield strength of the ∅8 deformed steel bars and the ∅5 mild steel stirrups was 570 MPa and 255 MPa, respectively. The mean compressive and tensile strength of the commonly used concrete of the original beams was measured from compression and splitting tests of six cylinders per testing, respectively, and presented in Table 2.

Table 1: Steel reinforcement and loading type of the tested specimens.

Beam name	Original beams			Jackets		Loading
	Bars (up)	Bars (bottom)	Closed stirrups	Bars (distributed)	U-formed stirrups	
M1 & M1-J R1 & R1-J	2∅8	4∅8	∅5/300	6∅5	∅5/80	Monotonic Repeated
M2 & M2-J R2 & R2-J	4∅8	4∅8	∅5/200	6∅5	∅5/100	Monotonic Repeated
M3 & M3-J R3 & R3-J	2∅8	4∅8	∅5/150	6∅5	∅5/100	Monotonic Repeated

Table 2: Mean compressive and splitting tensile strength of the commonly used concrete of the original beams and the SCC of the jackets.

	Commonly used concrete of the original beams	SCC of the jackets
Compressive strength (MPa)	25.57	40.10
Tensile splitting strength (MPa)	2.07	3.35

Further, mix design composition for casting one cubic meter of this ordinary concrete is summarized in Table 3 (kg/m^3).

2.2. Jacketed Beams. During the initial loading the original shear-dominated beams suffered severe diagonal cracking and exhibited brittle failure mode. Afterwards, all the damaged beams were rehabilitated using RSCC jackets. 25 mm thick jackets encased the bottom width and both vertical sides of the beams (U-formed jacketing). This way, all the retrofitted beams had the same rectangular cross-sectional dimensions (b_j/h_j = 175/225 mm) and the same effective depth (d_j = 205 mm), as shown in Figure 2. The total length of the jacketed beams remained the same as the length of the original beams (1.6 m).

The steel reinforcement of the jacket consists of small diameter ∅5 mild steel with average yield strength equal to 255 MPa. 6∅5 straight bars were distributed along the perimeter of the jacket as longitudinal reinforcement and ∅5 U-formed stirrups per 100 and 80 mm were placed as transverse reinforcement. Details of the jacketing reinforcement are displayed in Figure 2 and summarized in Table 1. The jacketed beams are denoted with "-J" in the codified names of the specimens; beams M1-J, M2-J & M3-J and R1-J, R2-J &R3-J were tested under monotonic and repeated loading, respectively.

It is mentioned that the total amount of the tensional longitudinal ratio of the jacketed beams was 0.67% (sum of the 4∅8 tension bars of the original beam and the 2∅5 tension bars of the jacket). Similarly, the total amount of the transverse reinforcement ratio was approximately 0.35% (sum of the closed stirrups of the original beam and the U-formed stirrups of the jacket).

The aim of the applied jacketing was focused on the increase of the amount of the provided transverse reinforcement in order to upgrade the shear resistance of the beams. Subsequently, jacketing intention was to fully restore the shear-damaged beams, to enhance their overall performance and, potentially, to alter the brittle failure mode of the original beams to a more ductile one.

Further, as mentioned before, the capacity of the available laboratory testing apparatus primarily dictated the dimensions and the reinforcement of the tested beams. An effort to model a realistic retrofitted beam of an existing RC structure in approximately one-half scale was made (e.g., the jacketing thickness of a realistic RC beam could be 50 mm).

It should be noted that the original beams sustained severe shear damages, spalling of concrete cover, and intense diagonal cracking during the initial loading. All the loose concrete fragments were completely removed and the missing parts of the beams were reconstructed by jacketing reformed and recasted by SCC. No special roughening of the surface of the damaged beams was performed prior jacketing construction.

Further, L-shaped mild steel dowels with 5 mm diameter were installed in the vertical sides of the initial beams in order to support the longitudinal bars of the jacket, as shown in Figure 2. Dowels were bonded by injected epoxy resin into 7 mm holes that were drilled before. The amount of the provided dowels was rather low; every side bar of the jacket had ∅5 dowels per 150 mm. No dowels have been installed at the bottom bars of the jackets. The main reason of the low amount of steel dowels provided is that the original beams suffered severe cracking and the installation of numerous of dowels by drilling may further deteriorate their damages. Steel bars, stirrups, and dowels were all welded together. The installation of the jacketing steel reinforcement is also shown in the photograph of Figure 3.

2.3. SCC Characteristics. Cast-in-place SCC was used to rehabilitate the damaged beams. Pouring of the SCC into the jacketing formwork is shown in the photographs of Figure 4. Mix design composition (in kg/m^3) and proportions for casting one cubic meter of SCC are summarized in Tables 3 and 4, respectively. The cement content was 356 kg/m^3 (305 kg of cement type CEM IV/B (W-P) 32.5 N and 51 kg of cement type CEM II/B-M 42.5 N). Fine aggregates (sand) and coarse aggregates with maximum diameter 8 mm were also used in the SCC mixture. Superplasticizer (Glenium

TABLE 3: Mix design composition and fresh properties of commonly used concrete of the original beams and of SCC of the jackets (kg/m^3).

	Commonly used concrete of the original beams	SCC of the jackets
CEM IV/B (W-P) 32.5 N	290	305
CEM II/B-M 42.5 N	45	51
Limestone filler	—	101
Limestone sand	—	882
River sand	1040	—
Coarse aggregates (4/8 mm)	360	800
Coarse aggregates (8/32 mm)	500	—
Water	186	193
Superplasticizer	3.5	11.93
Retarder	1.3	1.14
VMA	—	0.43
W/C	0.55	0.54
W/P	0.55	0.42
Slump (mm)	200	—
Slump flow D_m (mm)	—	780
T_{500} (sec)	—	2
Vf1 (sec)	—	12
Vf2 (sec)	—	15
L-Box	—	0.89

21), retarder (Pozzolith 134 CF), and viscosity modifying admixture (VMA, Rheomatrix 150) were also added in order to bring the required water reduction and fluidity, and to increase cohesion and segregation resistance [2, 3]. It is noted that the quantity of cement and filler, the small diameter aggregates, and the presence of VMA along with high-range water-reducing admixture can modify substantially the rheological properties of the hardened SCC [21].

The mean values of the cylinder compressive and splitting tensile strength of the used SCC are presented in Table 2 (mean values of six cylinders for each testing). The passing and the filling ability or "flowability" of the used SCC were assessed according to the European guidelines for self-compacting concrete [22] as shown in Figure 5 (slump flow test) and presented in Tables 3 and 5 (results of slump flow, T_{500}, V-Funnel, and L-box tests).

After SCC pouring, the final result was reasonably good. Limited superficial imperfections were observed after jacketing formwork stripping and they were fixed using high-strength, low-shrinkage, and rapid-hardening cement paste (EMACO S55) [23].

2.4. Loading Steps. The original beams M1, M2 & M3 and the corresponding jacketed beams M1-J, M2-J & M3-J were tested in monotonically increasing loading up to total failure. The original beams R1, R2 & R3 and the corresponding jacketed beams R1-J, R2-J & R3-J were tested under repeated loading with three and five steps of loading-unloading-reloading, respectively.

Original beams were designed to be shear dominated and expected to fail under shear. Prior to the final loading step till the ultimate failure, original beams R1, R2 & R3 were loaded and unloaded in two steps. In the first step, beams were loaded up till the visual detection of the first inclined cracking (onset of the shear cracking) that corresponds to approximately 50% of the ultimate applied load and unloaded to zero load. It is noted that the ultimate applied load has been determined by the monotonically tested corresponding beams. In the second step, beams were loaded up till the formation of a single sever diagonal crack, when the applied diagonal tension exceeded the concrete tensile strength, that corresponds to approximately 85% of the ultimate applied load and then unloaded to zero load. Finally, in the third loading step, original beams were loaded till failure. It should be mentioned that since all the original beams were designed to fail under shear and prior the development of any steel yielding, the steps of the repeated loading are considered in the elastic range of the experimental response.

Concerning the jacketed beams, RSCC jackets were designed in order for the retrofitted specimens to be flexure-dominated and, therefore, flexural behaviour was anticipated. This way, jacketed beams R1-J, R2-J & R3-J were loaded and unloaded in four steps prior to the final loading step till the ultimate failure. The first two steps were in the elastic range (prior yielding), whereas the third and fourth steps were in the inelastic range of the experimental response (after yielding of tension reinforcement). In the first loading step of the elastic range, beams were loaded up to approximately 50% of the applied load at yield and unloaded to zero load, while in the second step (also in the elastic range) beams were loaded up to approximately 85% of the yielding load and then unloaded to zero load. It is noted that the applied load at yield has been determined by the monotonically tested corresponding beams. In the third step, beams were loaded up beyond the yielding load and to overcome approximately 1.5 times the deflection at yield in the inelastic range (after yielding) of the response and then unloaded to zero load. In the fourth step (also in the inelastic range) beams were loaded up to a deflection approximately 8 times the deflection at yield and then unloaded to zero load. Finally, in the fifth loading step, jacketed beams were loaded up to failure.

The main objective of the aforementioned loading sequence was to obtain data on the influence of the repeated loading steps in the elastic and inelastic ranges on the effectiveness of the applied RSCC jacket.

2.5. Test Setup. The experimental setup of the tested beams is shown in Figure 1. Beams were edge supported on roller supports using a rigid laboratory frame. The imposed loading was applied using a steel spreader beam in two points in the midspan of the beams (four-point bending loading) with a shear span of $a = 600$ mm. The span to the effective depth ratio of the original and the jacketed beams equals $a/d_o = 3.43$ and $a/d_j = 2.93$, respectively.

Table 4: Mix design proportions for casting one cubic meter of SCC.

Cement	Water	Fine aggregate	Coarse aggregate	Filler	Superplasticizer	Retarder	VMA
1	0.54	2.48	2.25	0.28	0.0335	0.0032	0.0012

Table 5: Measures of the slump flow test of the SCC of the jackets.

	D1 (mm)	*D2* (mm)	Mean *D* (mm)
1st mixture	750	780	765
2nd mixture	750	800	775
3rd mixture	790	810	800

Loading was imposed consistently by a pinned-end actuator. Load was controlled and measured by a 200 kN load cell with an accuracy of 0.05 kN. The net midspan deflections of the tested beams were recorded by three LVDTs with 0.01 mm accuracy. One of them was placed in the midspan of the beams and the other two in the supports (see also Figure 1). Measurements of the applied load, P, and corresponding deflections, Δ, were read and recorded continuously during the tests.

3. Test Results and Discussions

It should be mentioned that the load bearing capacity of the jacketed beams, as summarised in Table 6, has been measured directly from the tests of the retrofitted specimens using the examined RSCC jacketing. The original beams have significantly been cracked and damaged due to the initial loading and they finally failed under shear in a brittle manner. However, the contribution of these shear-damaged beams on the overall capacity of the jacketed beams is nonnegligible since the original beams include a considerable amount of longitudinal reinforcement that has not been yielded during the initial loading.

Further, the compression zone of the midspan of the original beams remained in a rather good condition during the initial loading since the diagonal cracking was observed in the shear spans of the beams. Therefore, the concrete, the tension, and the compression steel bars of the original beams greatly influence the flexural capacity of the retrofitted specimens that consist of the initially damaged beams (core beam) and the relatively thin RSCC jacket. This critical issue has also been reported and verified from the test results of a previous relevant study that deals with the performance of jacketed reinforced concrete beams under bending [14].

3.1. Monotonically Tested Beams. Regarding the response of the original beams M1, M2 & M3, flexural cracks first formed from the bottom surface of the beams within the constant maximum moment region at midspan of the beams, when the applied load was varied from 12.1 to 13.7 kN that corresponds to an average shear stress of 0.28–0.31 MPa (onset of the flexural cracking). As the applied load increased, cracks spread out and gradually inclined cracks formed within the constant shear region at both shear spans of the beams. This first inclined crack developed at applied load of 28.3–32.0 kN that corresponds to a cracking shear stress of 0.65–0.73 MPa (onset of the shear cracking). When the load was sufficient to impose a diagonal tension greater than the concrete tensile strength (load was varied from 41.4 to 44.6 kN that corresponds to a shear stress of 0.95–1.02 MPa), the beams exhibited one severe diagonal crack. Afterwards, depending on the amount of the insufficient provided shear reinforcement of the beams, the applied load increased and the original beams inevitably failed suddenly and in a quite brittle manner along with a single diagonal shear crack. The peak applied load was measured 56.2–61.8 kN that corresponds to an ultimate shear stress of 1.28–1.41 MPa, as presented in Table 6.

The jacketed beams M1-J, M2-J & M3-J showed a completely different and ameliorated response. First flexural cracking was formed from the bottom surface of the beams within the constant maximum moment region at midspan of the beams, when the applied load was varied from 19.2 to 23.3 kN that corresponds to an average shear stress of 0.27–0.32 MPa (onset of the flexural cracking). As the applied load increased, flexural cracking spread out and only a few inclined cracks were formed. When the load was 69.4–70.8 kN that corresponds to a bending moment of 20.8–21.2 kN-m and to an average shear stress of 0.97–0.99 MPa the yielding of the tensional reinforcement was obtained, as shown in Figures 6 and 7 and presented in Table 6.

After yielding, the applied load slowly increased whereas the corresponding midspan deflection gradually enlarged resulting to a significant reduction of the after yielding stiffness of the jacketed beams in comparison with the initial elastic stiffness. This pure flexural response is also confirmed from the experimental curves of Figures 6 and 7. Progressively, some flexural cracks become wide and concrete crushing with associated spalling of the concrete cover in the compression zone was obtained at the ultimate flexural capacity of the beams. The maximum measured applied load was varied from 80.0 to 84.0 kN that corresponds to an ultimate bending moment of 24.0–25.2 kN-m and to an average shear stress of 1.11–1.17 MPa. Failure occurred at either final disintegration of the compressed concrete as a consequence of buckling of compression bars or the fracture of the jacketing tension bars or both. The observed maximum deflection was greater than 100 mm and the ratio of the deflection at failure to the deflection at yield point was varied from 19.4 to 23.2 (see the values of Δ_{max}/Δ_y in Table 6). These deflection ductility values indicate the enhanced ductile behaviour of the jacketed beams in comparison with the brittle nonductile response of the original beams.

From the experimental values of Table 6 and the response curves of Figure 7 it is obvious that a significant improvement of the load bearing capacity of the retrofitted beams with respect to the corresponding original beams has been

Table 6: Experimental results.

Beam name	V_y (kN)	$v_y = V_y/(bd)$ (MPa)	V_u (kN)	$v_u = V_u/(bd)$ (MPa)	$M_y = aV_y$ (kN-m)	$M_u = aV_u$ (kN-m)	M_j (kN-m)	Δ_{max}/Δ_y	Observed failure mode
M1	—	—	28.1	1.28	—	16.9	—	1.0	Shear
M1-J	34.9	0.97	42.0	1.17	20.9	25.2	8.3	23.2	Flexure
R1	—	—	27.9	1.27	—	16.7	—	1.0	Shear
R1-J	34.2	0.95	41.6	1.16	20.5	25.0	8.3	22.9	Flexure
M2	—	—	28.6	1.31	—	17.2	—	1.0	Shear
M2-J	34.7	0.97	40.0	1.11	20.8	24.0	6.8	21.7	Flexure
R2	—	—	28.5	1.30	—	17.1	—	1.0	Shear
R2-J	32.7	0.91	40.5	1.13	19.6	24.3	7.2	21.6	Flexure
M3	29.4	1.34	30.9	1.41	17.6	18.5	—	1.3	Shear
M3-J	35.4	0.99	41.5	1.16	21.2	24.9	6.4	19.4	Flexure
R3	—	—	29.1	1.33	—	17.5	—	1.0	Shear
R3-J	34.9	0.97	39.7	1.11	20.9	23.8	6.3	18.0	Flexure

Figure 3: Typical installation of the jacketing steel reinforcement (view from the bottom of the original damaged beam).

Figure 4: Formwork of the jacket and SCC pouring.

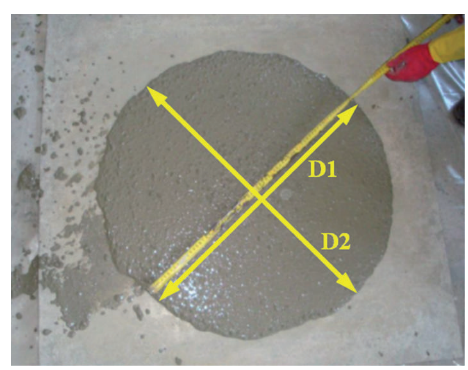


Figure 5: Slump flow test of the used SCC.

obtained. This increase of the maximum applied bending moment is also presented in Table 6 by the values of M_j that represents the difference of the flexural capacities between the jacketed and the corresponding original beam. Further, the overall structural performance of the jacketed beams is substantially ameliorated regarding the initial shear-damaged specimens since the jacketed beams exhibited pure flexural behaviour whereas the corresponding original beams demonstrated typical brittle shear response.

It is emphasized that although the ultimate load bearing capacities of the jacketed beams are greater than these of the original beams (see also Table 6 and Figure 7), the values of the average shear stress, $v = V/(bd)$, of the retrofitted beams are lower than these of the original beams (see also Table 6 and Figure 6). This is due to the increase of the cross-sectional dimensions of the jacketed beams ($b_j \times d_j = 175 \times 205$ mm) in comparison with the original dimensions of the beams ($b_o \times d_o = 125 \times 175$ mm).

3.2. Beams under Repeated Loading. The experimental behaviour of the original and the jacketed beams is presented in Figure 6 in terms of average shear stress versus midspan deflection curves. Further, flexural capacity and midspan deflection responses of the tested beams are compared in Figure 7. The experimental values of the applied shear force at yield point, V_y (if any was observed), the corresponding average shear stress at yield, v_y, the corresponding bending moment at yield, M_y, the maximum applied shear load, V_u (ultimate shear strength), the corresponding average shear stress at ultimate strength, v_u, and the corresponding bending moment at ultimate capacity, M_u, (flexural capacity) are also reported in Table 6.

The concluding response of the original beams R1, R2 & R3 under repeated loading was very alike with the response of the monotonically tested original beams. At the first

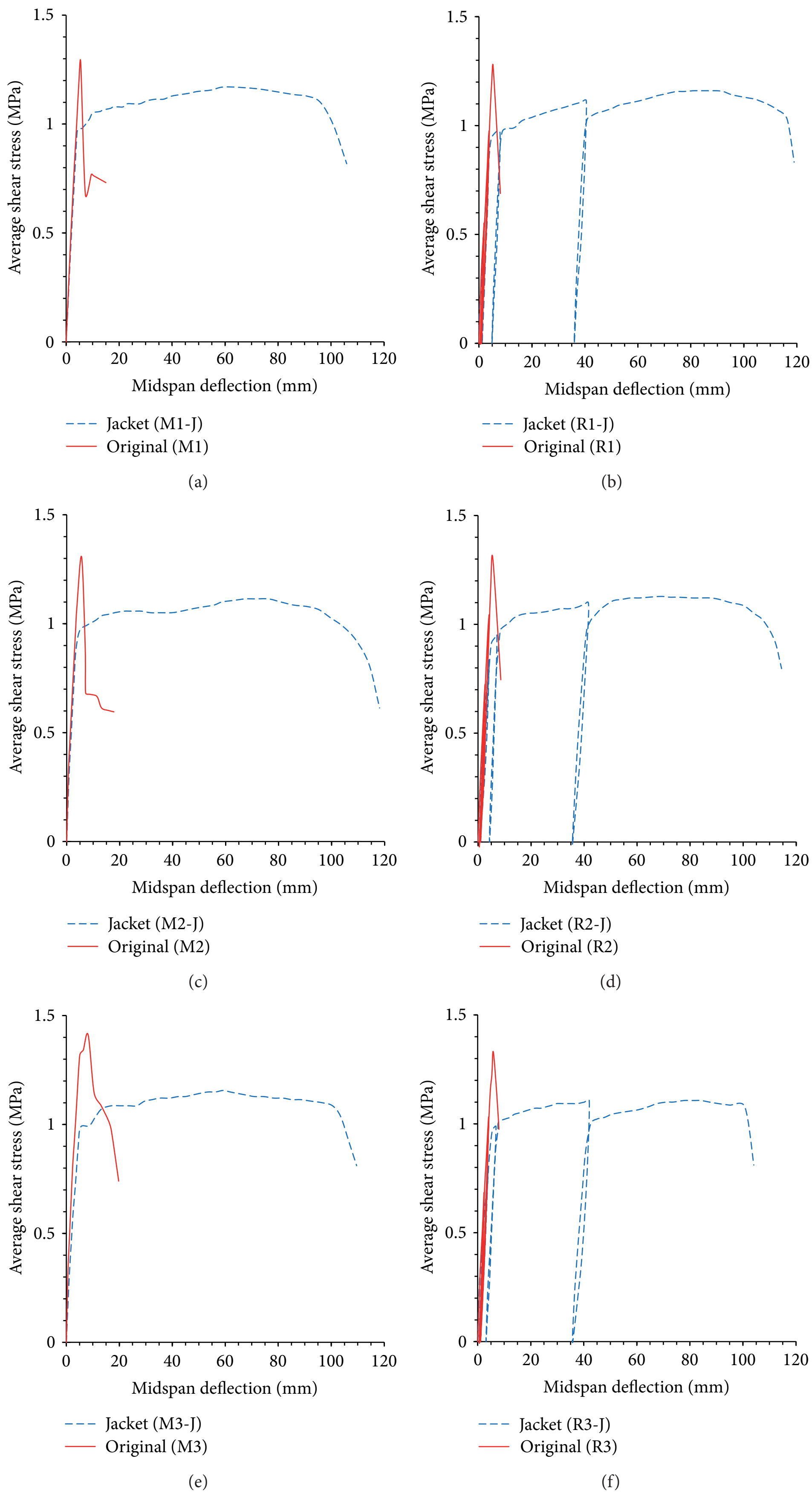


Figure 6: Experimental behaviour of the tested beams in terms of average shear stress versus midspan deflections.

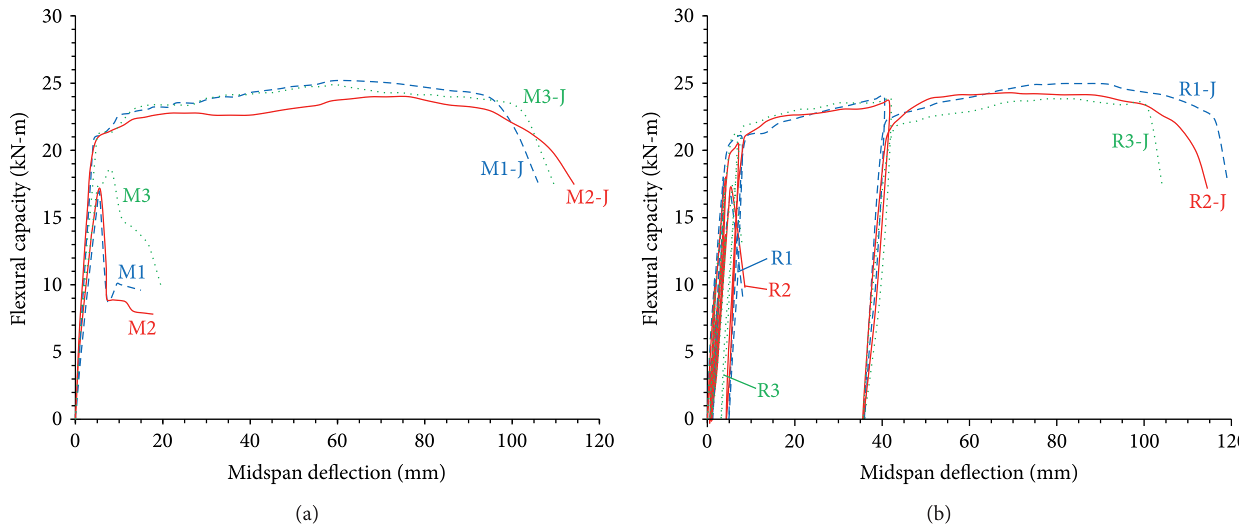
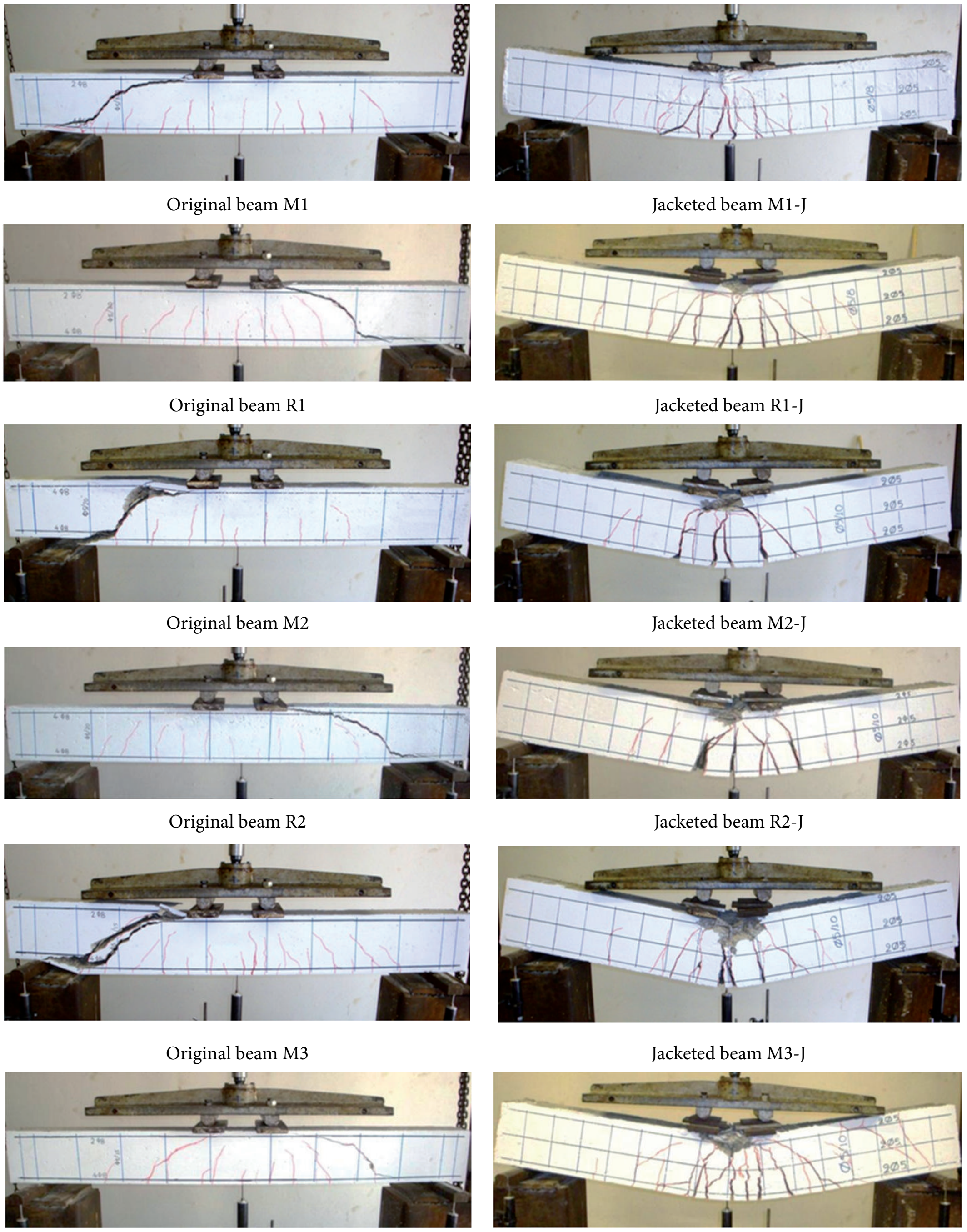


Figure 7: Comparisons of the flexural capacity versus midspan deflections curves of the tested beams.

loading step, flexural cracks initially formed from the bottom surface of the beams within the constant maximum moment region at midspan of the beams, when the applied load was varied from 13.1 to 13.6 kN that corresponds to an average shear stress of 0.30–0.31 MPa (onset of the flexural cracking). The increase of the applied load caused cracks to spread out and the first inclined cracks to be formed within the constant shear region of the beams. The end of the first loading step was determined by the visual detection of the first inclined crack (onset of the shear cracking) that developed at applied load of 27.1–31.6 kN that corresponds to a cracking shear stress of 0.62–0.72 MPa. After this peak load of the first loading step beams were unloaded to zero load and slight permanent deflections of 0.50–0.66 mm were measured. During the second loading step more inclined cracks were formed within the constant shear region at both shear spans of the beams while load increasing. Inevitably, when the applied load caused the imposed diagonal tension to be greater than the concrete tensile strength, a single sever diagonal crack formed. This indicated the end of the second loading step at an applied load that varied from 42.7 to 45.7 kN that corresponds to a shear stress of 0.98–1.04 MPa. After this peak load of the second loading step beams were unloaded to zero load and the permanent deflections were 0.92–1.06 mm. Finally, in the third loading step beams were loaded up to failure. During this final loading step the cracking pattern of the beams remained more or less the same without the formation of any new crack. All the original beams failed suddenly in a quite brittle manner along with a single diagonal shear crack when the ultimate applied load was 55.8–58.2 kN that corresponds to an ultimate shear stress of 1.27–1.33 MPa, as presented in Table 6.

The jacketed beams R1-J, R2-J & R3-J under repeated loading demonstrated an enhanced ductile response, as the jacketed beams under monotonic loading. During the first elastic loading step, the onset of the flexural cracking was observed at applied load equal to 19.7–22.3 kN that corresponds to an average shear stress of 0.28–0.31 MPa. The end of the first loading step was determined when the applied load reached a value approximately 50% of the applied load at yield, as measured from the monotonically tested retrofitted beams. This load was measured to be varied from 31.9 to 34.4 kN that corresponds to an average shear stress of 0.44–0.48 MPa. After this peak load of the first loading step beams were unloaded to zero load and slight permanent deflections of 0.59–0.62 mm were measured. In the second step, also in the elastic range, beams were loaded up to approximately 85% of the yielding load and flexural cracks spread out. A few inclined cracks were also formed within the constant shear region at both shear spans of the beams. The peak applied load of this second loading step was 55.7–59.7 kN that corresponds to an average shear stress of 0.78–0.83 MPa. After this point beams were unloaded to zero load and the measured permanent deflections were 0.98–1.20 mm. During the third loading step beams were loaded up to obtain the yielding of the tensional reinforcement and to a deflection approximately 1.5 times the deflection at yield (inelastic range after yielding). The applied load at yield varied from 65.3 to 69.8 kN that corresponds to a bending moment of 19.6–20.9 kN-m and to an average shear stress of 0.91–0.97 MPa, as shown in Figures 6 and 7 and presented in Table 6. After the peak deflection point of the third loading step, beams were unloaded to zero load and the permanent deflections were varied from 3.13 to 4.91 mm. The fourth loading step was also in the inelastic range and beams were loaded up to a deflection that varied from 40.53 to 41.70 mm (approximately 8 times the deflection at yield) and then unloaded to zero load. During this fourth loading step flexural cracks become wide and a reduction of the after yielding stiffness of the beams was observed, as it was expected. Finally, in the fifth loading step, jacketed beams were loaded up to total failure. Concrete crushing along with concrete spalling in the compression zone was obtained at the ultimate flexural capacity of the beams. The maximum



Original beam M1 | Jacketed beam M1-J
Original beam R1 | Jacketed beam R1-J
Original beam M2 | Jacketed beam M2-J
Original beam R2 | Jacketed beam R2-J
Original beam M3 | Jacketed beam M3-J
Original beam R3 | Jacketed beam R3-J

Figure 8: Cracking patterns of the original and the jacketed beams.

applied load was measured 79.4–83.2 kN that corresponds to an ultimate bending moment of 23.8–25.0 kN-m and to an average shear stress of 1.11–1.16 MPa. Failure occurred at either final disintegration of the compressed concrete as a consequence of buckling of compression bars or the fracture of the jacketing tension bars or both. Maximum deflections were measured to be greater than 100 mm and the deflection ductility varied from 18.0 to 23.2 (see the values of Δ_{max}/Δ_y in Table 6), verifying the preferable flexural behaviour of the jacketed beams.

The comparisons between the monotonically tested beams and the corresponding specimens suffered repeated loading steps prior failure and showed that the influence of the repeated loading to the ultimate capacity is minor. Slight till neglected reductions of the flexural strengths of the jacketed beams R1-J, R2-J & R3-J (subjected to repeated loading) can be observed with respect to the corresponding jacketed beams M1-J, M2-J & M3-J (subjected to monotonic loading).

3.3. Cracking Patterns and Failure Modes. The cracking patterns at failure of the original and the jacketed beams are displayed in the photographs of Figure 8 and summarized in Table 6. It can be observed that all the original beams exhibited diagonal cracking and quite brittle shear failure (see the left photographs in Figure 8). On the contrary, jacketed beams exhibited pure flexural cracking patterns and ductile failure mode (see the right photographs in Figure 8). During the retest, the retrofitted specimens developed flexural cracks and showed an increasing after yield behaviour till the ultimate capacity.

3.4. Comparisons with Test Data of the Literature. The experimental results derived from this study are compared with the available test data of previously published works from the literature [10, 13–15] in Figure 9. Figure 9 illustrates 27 test data points from these experimental researches in terms of the ratio $P_{\text{jacketed}}/P_{\text{original}}$ and $(A_c f_c A_s f_y)_{\text{jacketed}}/(A_c f_c A_s f_y)_{\text{original}}$ where P_{jacketed} and P_{original} are the ultimate load bearing capacity of the jacketed and the original beam, respectively, and A_c, f_c, A_s, and f_y are the area of the cross-section, the concrete compressive strength, the area of the longitudinal steel reinforcement, and the steel yield strength, respectively, of the jacketed and the original beam.

It is noted that the experimental results used in Figure 9 consist of RC jacketed beams (18 data points) and columns (9 data points) under monotonic, repeated, or cyclic imposed deformations that exhibit flexural performance. The comparison of these test data indicates that the measured increase of the load bearing capacity due to the application of RC jacketing seems to be approximately proportional to the ratio $(A_c f_c A_s f_y)_{\text{jacketed}}/(A_c f_c A_s f_y)_{\text{original}}$. This ratio is evaluated by the area and the strength of the concrete used and the longitudinal steel provided to the jacketed beam and to the original beam. Therefore, the aforementioned ratio expresses the increase of the cross-sectional dimensions and the amount of the steel bars due to the application of RC jacketing.

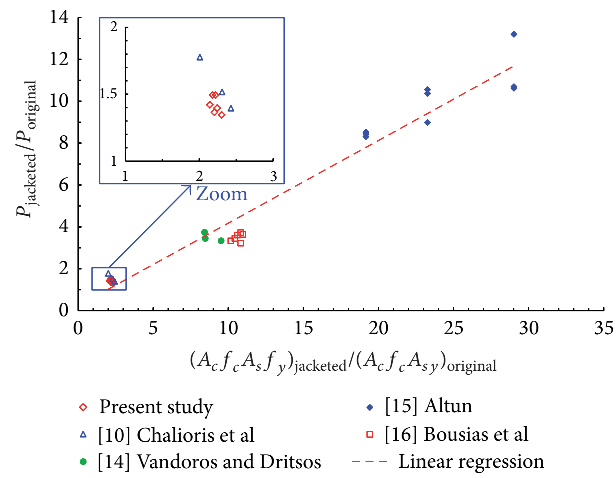


FIGURE 9: Comparisons between the experimental results derived from this study (6 data points) and the literature [10, 13–15] (21 data points).

4. Summary and First Conclusions

The application of an RSCC jacket to damaged shear-dominated RC beams under monotonic and repeated loading is experimentally investigated. The examined jacket encased the bottom width and both vertical sides of the specimens (U-formed jacketing), consisted of small diameter steel bars and U-formed stirrups, and was made of SCC. The mean compressive and splitting tensile strength of the used SCC was 40.10 MPa and 3.35 MPa, respectively.

From the experimental results presented in this study it can be concluded that the applied RSCC jacketing technique proved to be a reliable and effective method for the rehabilitation of shear-damaged RC beams. The load bearing capacity and the overall structural performance of the jacketed beams was fully restored and ameliorated with respect to the original specimens. The increase of the experimentally measured ultimate bending moment of the tested beams due to the application of the RSCC jackets ranges between 35% and 50%. This increase seems to be higher in the original beams with low amount of stirrups and to be reduced as the steel ratio of the stirrups increases. The mean value of the flexural strength of the jacketed and the original beams is 24.5 kN-m and 17.3 kN-m, respectively. Further, the ultimate shear load of the jacketed beams ranges from 39.7 kN to 42.0 kN, whereas the shear capacity of the original beams is approximately 30% lower and ranges between 27.9 kN and 30.9 kN. However, the measured average shear stress of the jacketed and the original beams is 1.14 and 1.32, respectively, since the cross-sectional dimensions of the jacketed beams were enlarged.

Furthermore, all retrofitted beams failed, as intended, in a ductile manner exhibiting a pure flexural behaviour whereas the corresponding original beams demonstrated typical brittle shear response. It is stressed that the values of the deflection ductility of the jacketed beams range between 18.0 and 23.2, whereas all the original beams exhibited brittle response and the ratio of the ultimate deflection to the deflection at yield varies from 1.0 to 1.3.

The influence of the imposed repeated loading to the ultimate shear strength of the original beams and to the flexural behaviour of the jacketed beams proved to be of minor importance since slight reductions of the potential capabilities of the examined beams were obtained. More experimental work is needed to quantitatively verify and to examine more structural parameters that might affect the effectiveness of RSCC jacketing.

Abbreviations

b, h: Width and height of the cross-section of a beam
d: Effective depth of a beam
b_o, h_o: Width and height of the cross-section of the original beams equal to 125 mm and 200 mm, respectively
d_o: Effective depth of the original beams equal to 175 mm
b_j, h_j: Width and height of the cross-section of the jacketed beams equal to 175 mm and 225 mm, respectively
d_j: Effective depth of the jacketed beams equal to 205 mm
a: Shear span of the beams equal to 600 mm
$D1$, $D2$: Measured diameters in the slump flow test
D: Average diameter in the slump flow test equal to $(D1 + D2)/2$
D_m: Mean diameter of the measurements in the slump flow tests
P: Applied load
P_y: Applied load at yield
P_u: Ultimate applied load
V_y: Shear load at yield equal to $P_y/2$
V_u: Ultimate shear load equal to $P_u/2$
M_y: Bending moment at yield equal to $V_y \times a$
M_u: Ultimate bending moment equal to $V_u \times a$
M_j: Bending moment increase due to the jacketing
v_y: Average shear stress at yield equal to $V_y/(bd)$
v_u: Average shear stress at ultimate equal to $V_u/(bd)$
$Vf1$, $Vf2$: Flow time (rate of flow) that assesses the viscosity/flowability of the SCC using the V-funnel test
L-Box: Passing ratio that assesses the passing ability of the SCC using the L-box test
T_{500}: Time during the slump flow test that assesses the viscosity/flowability of the SCC
Δ: Midspan deflection
Δ_y: Midspan deflection at yield
Δ_{max}: Midspan deflection at failure.

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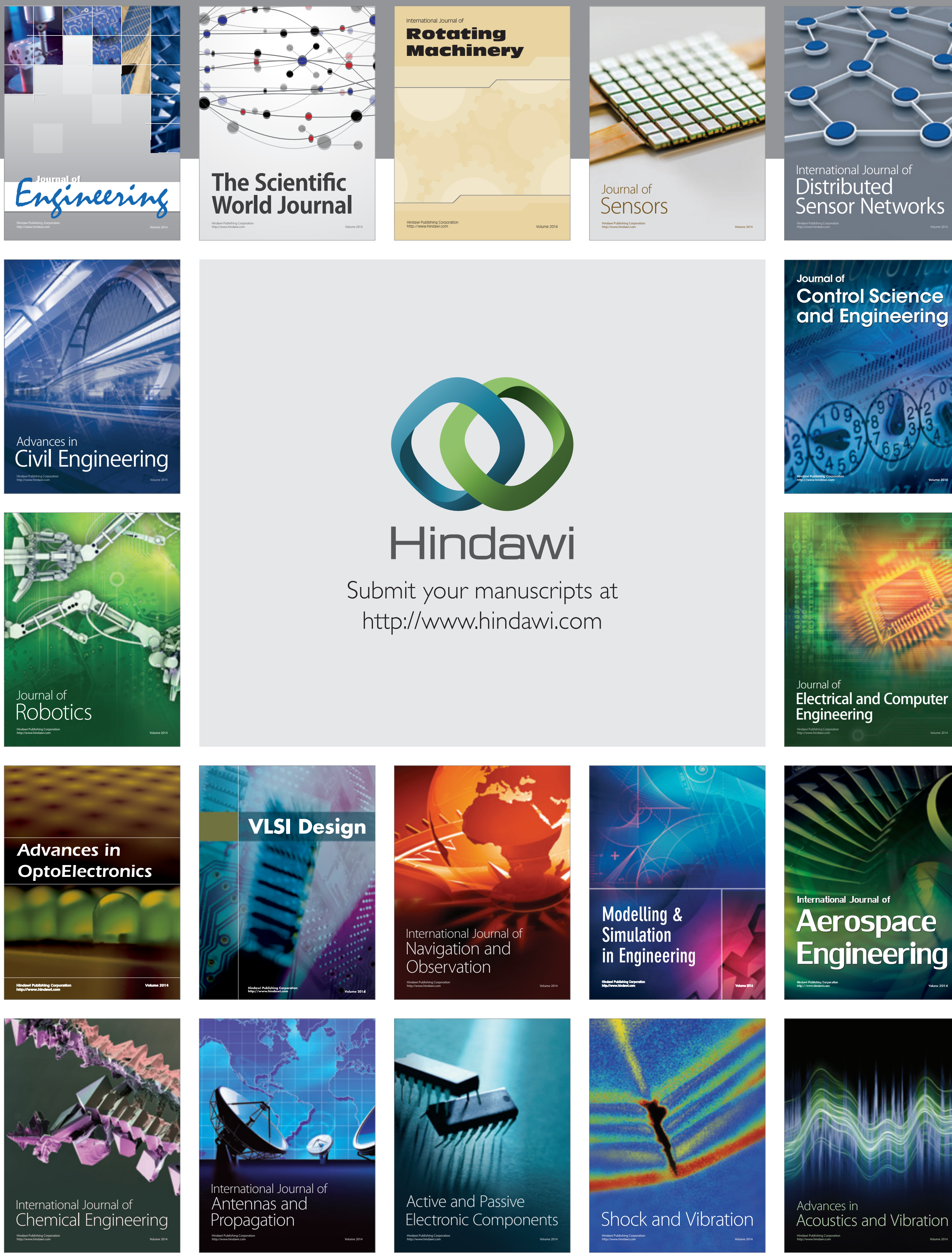
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