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Corrosion effect of the main rebar and stirrups on the bond strength of RC beams

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ABSTRACT

Spliced region is a place where the concrete-rebar bond plays a significant role, and reduced bond strength in this region negatively affects the structure safety and integrity due to corrosion. This research has studied the combined corrosion effects of the main reinforcements and stirrups in the spliced region on the concrete-rebar bond strength in lap-spliced beams. A total of 15 lap-spliced RC beams with different stirrup spacing in the spliced region failed under 4-point bending; tensile bar and stirrup corrosions were the variables in this study. Finally, Response Surface Methodology (RSM) was used for estimating the relative bond strength of this beams. According to the results, adding corroded stirrups in the spliced region will cause negative effects on the bond strength in beam specimens via combined tensile bar-stirrup corrosion in the spliced region. Gradients in the descending part of the curve for relative bond strength versus corrosion were calculated at −0.0154, −0.016 and −0.017 when stirrups are 1, 2 and 3, respectively. Also, beams with 25% corrosion have the largest increase in the stirrup-induced bond strength. The results show that the model presented by RSM is in good agreement with the experimental results.

1. Introduction

When a bar is corroded, its volume expands several times due to the corrosion composition causing its surrounding concrete to undergo tensile stress [1–5], cracking and splitting. As a result, the chlorine ions will reach the bar surface faster and speed up its corrosion process.

The force created on the rebar has a horizontal component (the bond force) and a vertical one that causes the concrete to expand and split. The mechanical interaction, chemical adhesion and friction highly affect the bond between the concrete and rebars. In deformed bars, mechanical interaction highly affects the bond because the concrete and stirrups confine the bars [6].

Moodi et al. [7] believe that tests that can determine the bond strength generally include the “Actual Beam Test”, “Pullout and End-beam Test, and “Tension Stiffening Test”. Corrosion reduces both the bar cross-section and the bond between the bar and concrete, but the reduction is more noticeable in the bond strength. According to Zhao et al. [8] study, when there is a reduction of 14% in corrosion, the bar section is reduced by 14%, but the bond strength reduction is about 80 to 90%. It has been shown in some studies [9–12] that the ultimate bond strength itself is highly affected by corrosion; bond strength will be reduced significantly by high corrosion values, but may increase by its low values.

Some articles that have employed the Pullout Test to study how corrosion affects the bond strength are Lee et al. [1], Al-Sulaimani et al. [9], Law et al. [11], Tondolo [12], Zhang et al. [13–14] and Yalciner et al. [15]. Al-Sulaimani et al. [9] investigated the effect of corrosion on the bond strength between concrete with polypropylene fibers and rebar. It has been found that polypropylene fibers in concrete improves the bond strength of concrete, especially at postcracking levels of corrosion. Tondolo [12] showed an initial increase in bond efficiency from 0% to 2% levels of corrosion in specimens confined by stirrups, whereas a substantial uniformity of the bond strength level was maintained for higher levels. The variables in Yalciner et al. [15] study were concrete cover, compressive strength and corrosion rate. The results showed that the effect of compressive strength is greater than the concrete cover to prevent corrosion. The stirrup confinement effect on the bond strength has been studied by Lee et al. [1] who showed (in stress-slip curve) that beyond the maximum strength, specimens equipped with stirrup confinement experienced more residual stress than those without it. Using the Beam-end Test, Law et al. [11] studied the effects of stirrup confinement and showed that: 1) it increased the bond strength

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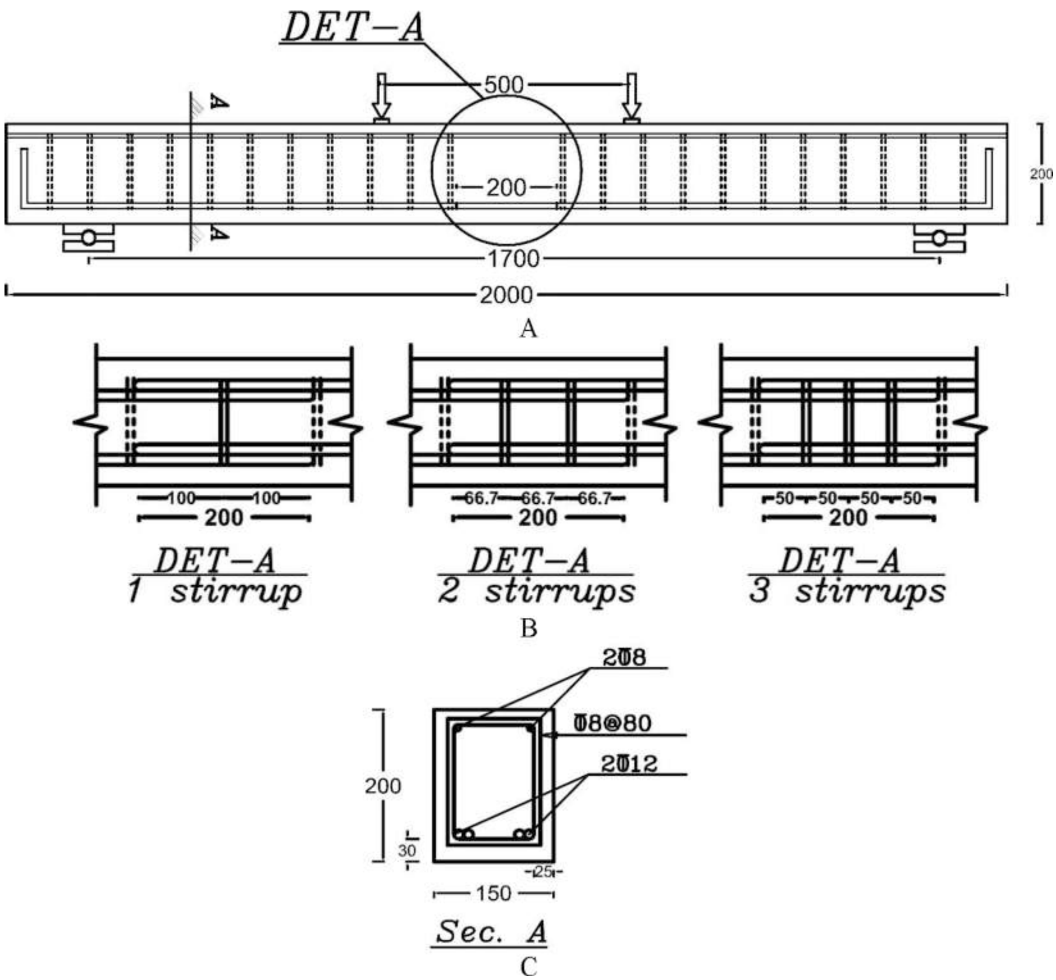


Fig. 1. Details of specimens: (A) Casting and position of testing, (B) Sectional area, (C) Splice region.

(when cracks had equal widths); and 2) stirrup effects were reduced when there was more concrete cover). Zhang et al. [14] conducted a research to study how corrosion affected strain-rate bond strengths, and found that specimens with no stirrups experienced a little increase in the bond strength when the concrete cover was increased, but stirrups highly increased the bond strength. However, some studies performed with the Pull-out Test showed that stirrups had no effects on the bond strength of corrosion-affected bars [16,17]. A push-out test was conducted by Sanz [18], revealing that corrosion affected the residual stress after the peak load.

In 2019, a pull-out test was used to investigate the bond strength of the recycled concrete reinforced with corroded and non-corroded bars, and the results showed that the bond strength behavior of the recycled concrete was significantly affected by corrosion [19]. Hanjari et al. [20] employed the beam-end test to study the effects of severe corrosion on the bond behavior of the main bar with and without stirrup corrosion, and observed a complex failure mode in specimens with joint longitudinal bar-stirrup corrosion. In 2019, Lin et al. [21] used the pull-out test with such variables as the thickness of the concrete cover, stirrup spacing, and corrosion rate to study the corrosion effects of the main bar and stirrups on the concrete-bar bond strength. They found that the combined tensile bar-stirrup corrosion enhanced the bond strength reduction compared to the longitudinal bar corrosion. They also presented a model, for the first time, to estimate the bond strength of specimens with combined longitudinal-transverse bar corrosion.

Effects of corrosion on the bond strength have been investigated through the Tension Stiffening Test in Shayanfar and Ghalenovi [10], Amleh and Mirza [22], Dai et al. [23], Aryanto and Shinohara [24] and Kim et al. [25]. Using 58 cylindrical RC specimens, Shayanfar and Ghalenovi [10] investigated the effect of corrosion on the tensile behaviour of RC members. They provided relationships for estimating the average crack spacing, bond strength and equivalent cross-section area of reinforcement. Amleh and Mirza [22] shown that in the tension tests simulating severe localized corrosion, the bond strength and the number of transverse cracks decreases as the level of corrosion increases until it becomes negligible. Dai et al. [23] studied effects of stirrups on the bond strength of corrosion-affected bars. Four phases of corrosion locations and three types of corrosion levels for each corrosion phase were investigated by the application of Tension Stiffening Test in the study of Kim et al. [25]. They showed that the slope of the ratio of maximum weight loss percentage and average weight loss percentage tend to decrease with an increase of the length of corroded area.

A number of studies have focused on the application of the actual beam test for the corrosion effects on the bond strength, less than those which used other tests (Lin and Zhao [6], Moodi et al. [7], Zhao et al. [8], Mangat and Elgarf [26], Al-Hammoud et al. [27], Sajedi and Huang [28] and Shihata [29]).

To study the effects of corrosion, Zhao et al. [8] utilized no-splice beams and showed that the bond strength was more than that obtained from the pullout test, mainly because of the lateral pressure of the supports on the longitudinal bar.

In 2010, Al-Hammoud et al. [27] used beams with no splices to see how stirrup/support confinement affected the bond strength between the concrete and bars, and showed that if the stirrup spacing is reduced, there will be an increase in the bond strength and, hence, the failure mode will change; also, when the stirrup spacing is large, an increased

Fig. 2. Stirrups: A. Painted and insulated stirrups and B. Intact stirrups.

development length will not affect the bond strength.

Lin and Zhao [6] carried out a research in 2016 and showed that in no-splice beams wherein the longitudinal bars were corroded, stirrups affected the bond strength; the corrosion-caused crack propagation was slow with smaller stirrup spacing, and the bond strength was reduced with larger stirrup spacing. The few studies that have used lap-spliced beams to see how corrosion affects the bond strength have eliminated the support-caused confinement effects because such beams have the splice in their mid-span. Sajedi and Huang [28] used the stress-slip behavior to study the bending behavior of beams with and without splice. In a lap-spliced beam test, to study the effects of corrosion on the bond strength, Shihata [29] employed such variables as the corrosion and concrete cover thickness (t) to bar diameter (d) ratio, and showed that both *t* and *d* affected the bond strength of the corroded bars (the stirrup-caused confinement effects in the lap spliced region were negligible). In an effort to examine how the corroded lap-spliced beam's bond strength was affected by stirrup spacing (only longitudinal bars were corroded; stirrups were not), Moodi et al. [7] showed that if stirrups in the spliced region were increased, the energy dissipation potential, ductility, and bond strength were increased too. They also found that) if corrosion was increased, the splice performance was more affected by stirrups. This paper considers corrosion and stirrup spacing (in the spliced region) as variables and studies how the combined tensile bar-stirrup corrosion affects the spliced region in RC beams.

The RSM is a powerful statistical and mathematical method that estimates the output parameters (responses) using a function relating the input parameters. This method was adopted by Box and Wilson [30] for different subjects. In previous studies, RSM has been widely used in engineering [31–35].

This research is aimed to study the joint corrosion effects of the tensile bars and stirrups of the spliced region in lap-spliced RC beams through the corrosion and stirrup spacing in the spliced region as variables. It is worth noting that while previous studies have not sufficiently addressed the effects of high corrosions on the bond strength, the present research has tried to compensate for the issue. Using the RSM method, a quadratic equation was presented to estimate the relative bond strength of lap-spliced RC beams with the joint corrosion effects of the tensile bars and stirrups. Finally, since materials/specifications of this study did not differ from those of Moodi et al. [7], effects of the tensile bar corrosion were compared with those of the combined tensile bar-stirrups. Results of this study showed that if the number of stirrups was increased in the spliced region, the bond strength in a combined corrosion state would be affected negatively; in specimens with more stirrups, the relative bond strength-corrosion curve lay below that of specimens with fewer stirrups – a result different from that of Moodi et al. [7] who studied corrosion effects of only longitudinal bars. Also, application of the proposed model by using RSM for estimating relative bond strength of these beams is suitable.

2. Experimental program

2.1. Test specimens

Fifteen 2000 mm-long RC beams with lap-splice and 200 × 150 mm in sectional area underwent 4-point bending tests; the two compressive bars (8 mm in dia.) were continuous and the two tensile bars (12 mm in dia.) were lap-spliced in the mid-span. Stirrups (8 mm in dia.) were spaced 80 mm center-to-center outside the splice not to let shear failure to occur and L_d (splice length) was 20 cm to ensure the bond failure (According to ACI 318–11 [36], neglecting corrosion). Fig. 1 shows the spacing and net bending length of the supports and dimensions of the specimens.

In this study, variables in the spliced region were: 1) number of stirrups (1, 2 and 3 with 100, 66 and 50 mm spacing, respectively), and

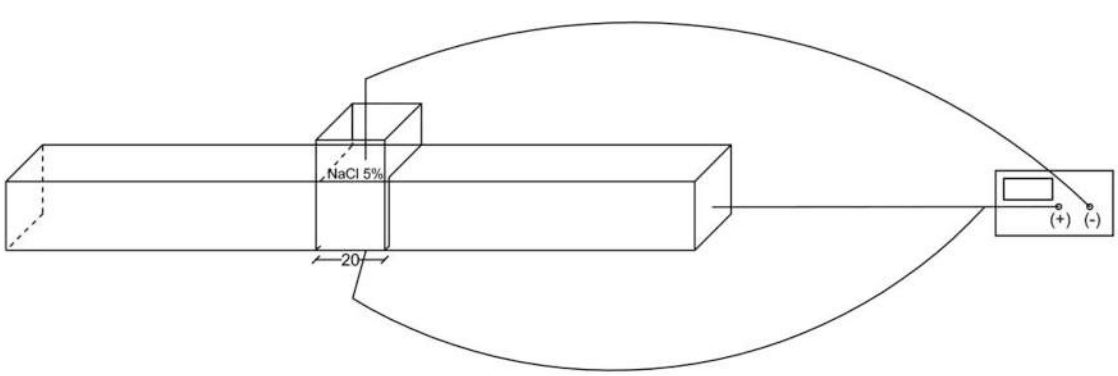


Fig. 3. System's electrical connections.

Table 1
Actual corrosion (%).

G3S2C25	G3S2C10	G3S2C5	G3S2C2	G3S1C25	G3S1C10	G3S1C5	G3S1C2	Specimen
21.77	10.41	5.81	2.33	17.97	9.73	5.31	2.07	Actual corrosion of tensile bars
22.31	11.07	5.63	2.85	21.03	10.11	5.55	2.23	Actual corrosion of stirrups
				G3S3C25	G3S3C10	G3S3C5	G3S3C2	Specimen
				19.19	10.28	4.14	1.61	Actual corrosion of tensile bars
				21.27	10.56	4.20	1.95	Actual corrosion of stirrups

2) combined tensile bar-stirrup corrosion (0, 2, 5, 10 and 25 percent). Notably, earlier studies have not addressed high corrosion rates, but this study has considered a 25% rate for this issue. In G3SbCi, the specimen name, *b* and *i* are the number of stirrups and corrosion of tensile bars and stirrups in the spliced region, respectively.

2.2. Materials specifications

Experimental process, the used concrete mix and type of aggregates follow those in Moodi et al. [7]. To prevent stirrup corrosion outside the spliced region, bars were epoxy painted, and to prevent current flow, they were insulated with electric glue where they were connected to tensile bars (Fig. 2-A). To let stirrups become corroded in spliced region, painting and insulation were omitted and they were used intact.

2.3. Accelerated corrosion

To investigate the effects of corrosion on the bond between the concrete and rebars, it is best to use the natural corrosion (it occurs over the years); however, what researchers do to expedite the process is to use the accelerated form that involves applying current to specimens in a 5% NaCl solution. According to Fig. 3, to corrode the bars and stirrups, small NaCl solution basins were made in the spliced region (200 mm in the mid-span) so that the solution could touch the beam on three sides; corrosion rates used for tensile bars and stirrups were 2, 5, 10, and 25%.

Faraday’s law was applied to calculate the time needed to apply different corrosion currents. In the present study, this time is calculated based on the introduced equation in Moodi et al. [7].

El-Maddaway and Soudki [37] showed that since the width of cracks and strain response caused by corrosion will sharply rise due to elevated corrosion current (above 200 μA/cm^2), corrosion products differ morphologically from those of the natural corrosion when the applied current density is high.

According to Saifullah and Clark [38], corrosion values of more than 250 μA/cm^2 can affect the structure more negatively than the normal corrosion. Thus, to produce natural corrosion through accelerated corrosion in the present study, the current density was assumed to be 190μA/cm^2.

In the spliced region, the 4 tensile bars and stirrups and the stainless steel inside the NaCl solution basin underwent the corrosion current (to act as anode and cathode, respectively). After finishing tests on beams, removing the corroded tensile bars and stirrups, cleaning them by pickling and weighing them according to ASTM G1-03 [39], corrosion was calculated by the equation presented in Moodi et al. [7].

Table 1 shows the average corrosion of the stirrups and tensile bars separately for each specimen.

2.4. Equipment and loading method/pattern

1700 mm-long, simply supported specimens underwent the 4-point bending test. A jack transferred the load to a distributor (rigid steel beam) and to the specimen as two concentrated loads with a distance of 500 mm. A load-cell placed between the jack and rigid beam and two LVDTs measured the applied load and mid-span deflection, respectively, and a data logger recorded the general information.

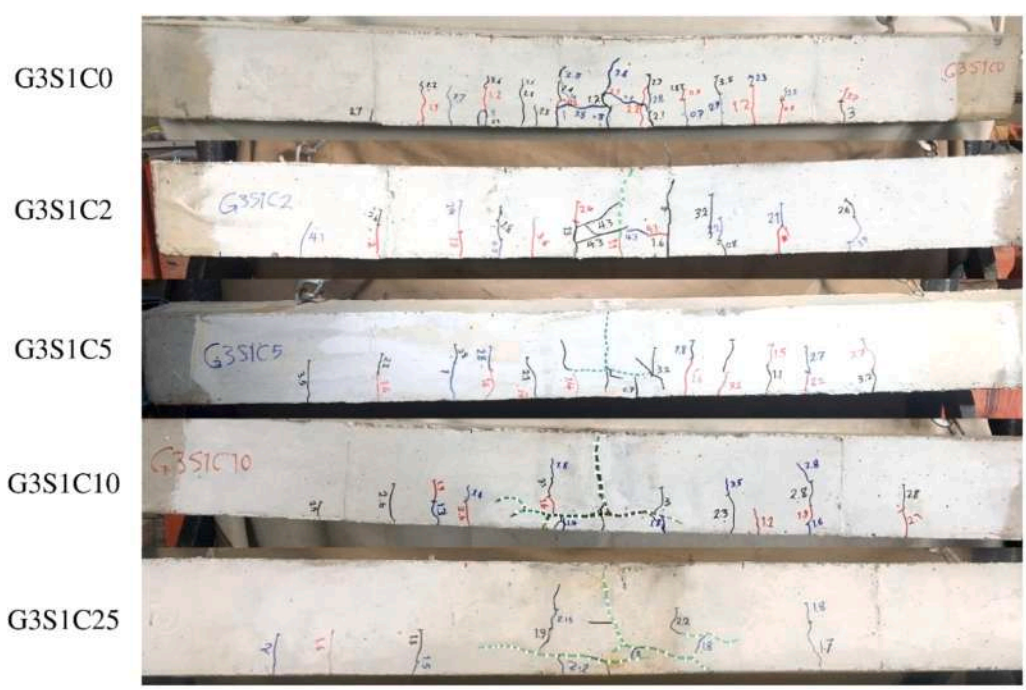


Fig. 4. Cracking pattern (specimens with 1 stirrup).

Fig. 5. Cracking pattern (specimens with 2 stirrups).

Fig. 6. Cracking pattern (specimens with 3 stirrups).

3. Results and discussion

3.1. Corrosion and its resulting cracks

Cracking commencement time for all specimens was about 8 days. It could be clearly observed how corrosion formed products and cracks and how the materials reached the surface of all specimens from within these cracks during the application of the current. A comparison of the results of the present study with those of Moodi et al. [7] reveals that the time needed for corrosion-induced cracks to form in specimens with combined tensile bar-stirrup corrosion is less than those with only tensile bars. In specimens with one stirrup in the spliced region, cross-shape (+) corrosion-induced cracks were formed along the longitudinal and transverse bars. Also, in those with more stirrups in the spliced region and higher corrosion, X-shape corrosion-induced cracks were formed on the specimens' lateral sides. It is worth mentioning that most specimens

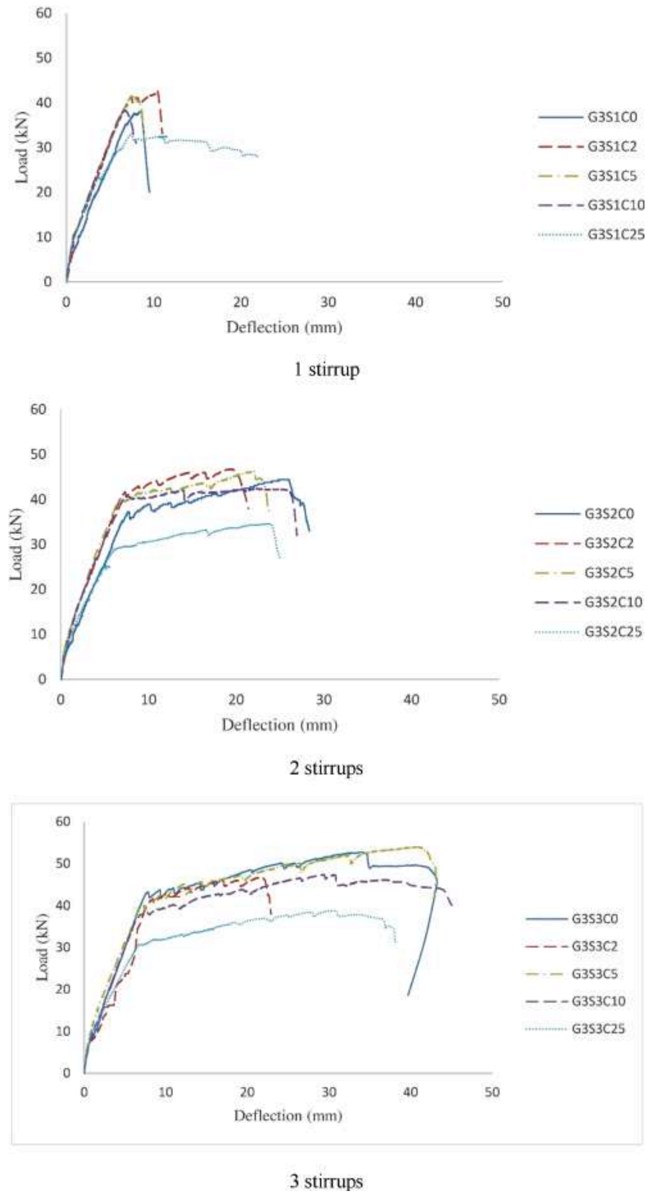


Fig. 7. Displacement-load diagram.

had corrosion-induced cracks in both longitudinal and transverse directions (dashed line in Figs. 4–6). After finishing tests on the beams, the actual corrosion (Table 1) was calculated by pulling out (of the concrete) and cleaning the corroded bars to perform according to ASTM G1-03 [39].

3.2. Load-induced crack patterns and failure modes

All specimens failed in the splice region because of short splice length (cracking pattern is shown in Figs. 4–6); corrosion- and load-induced cracks are shown with dashed and continuous lines, respectively.

The first bending cracks outside the spliced region were formed in specimens corroded at larger loads compared to non-corroded ones. Stirrup spacing in this region had no effects on the first bending crack load outside this region which means that in similar corrosions, the first bending crack load outside the splice of specimens with different stirrups is approximately the same. Importantly, in specimens with X-shape corrosion-induced cracks or those that have corrosion-induced cracks along longer splices, loading-induced cracks were not formed along the splice.

With more corrosion, the load-induced cracks were reduced (more evident in specimens with 1stirrup) and with more stirrups (in the spliced region), the load-induced cracks increased too.

3.3. Load-displacement curve, maximum strength

Fig. 7 shows the mid-span load–displacement curve for each set of specimens with equal number of stirrups and different corrosions, and Fig. 8 shows the maximum load tolerated by beams; the latter also shows Moodi et al.'s [7] results of specimens with no stirrups in the spliced region (group G1) to compare the effects of using corroded stirrups in this region. According to Figs. 7 and 8, small corrosions (2–5%), compared with the no-corrosion state, increase the bond strength, which is higher for specimens with fewer stirrups in the spliced region; in specimens with 1, 2, and 3 stirrups in the spliced region, a 2% corrosion caused a raise of about 12.6, 5.2 and 3.7% in the bond strength in specimens with 1, 2, and 3 stirrups in the spliced region, respectively. Since these results contrast with those of Moodi et al.'s [7] on the tensile bar corrosion, it can be concluded that more stirrups in the spliced region in corrosive environments can have negative effects on the bond strength.

How the bond strength of a lap-spliced beam is affected by the stirrup spacing, hence corrosion, can be understood better if one referred to Fig. 9 that depicts the relative bond strength-corrosion diagram for the specimens of the current study and Moodi et al.'s [7] no-stirrup specimens. R_τ (relative bond strength) is found calculated through $\tau_u(c)$ and $\tau_u(0)$ as the bond strength of the corroded and corresponding non-corroded specimens, respectively:

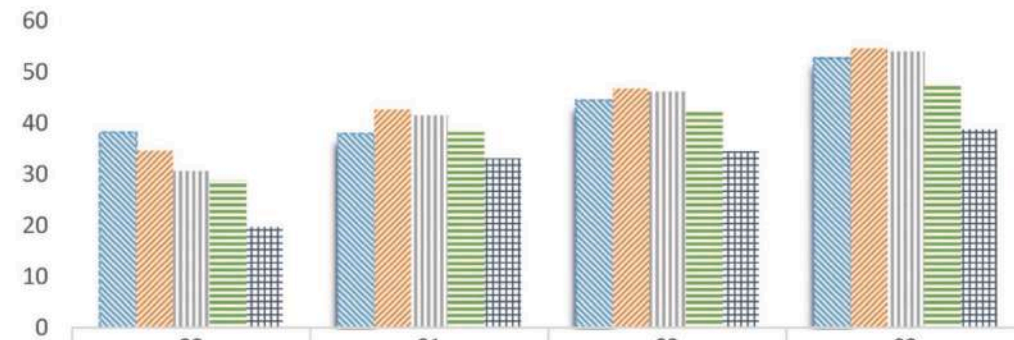
$$R_\tau = \frac{\tau_u(c)}{\tau_u(0)} \tag{1}$$

By fitting the best linear equation in the descending branch of the curve of the relative bond strength versus corrosion, the gradients for 0, 1, 2, and 3 corroded stirrups in the spliced region were found to be −0.0198, −0.0154, −0.016 and −0.017, respectively.

A comparison of the specimens of the present study with those of Moodi et al.'s [7] (with no stirrups in the spliced region) shows that a larger number of corroded stirrups (in the spliced region) results in the reduction of the gradient of the descending branch of the curve of the relative bond strength versus corrosion compared to no-stirrup specimens. However, if corroded stirrups vary in the spliced region, the difference between specimens will be none. It was shown in Moodi et al.'s [7] study that if merely tensile bars becomes corroded in the spliced region, adding stirrups will reduce the gradient of the descending branch of the curve of the relative bond strength versus corrosion, and the curve of specimens with more stirrups will lie above that of specimens that have fewer stirrups. Nevertheless, in the specimens of the present research where the combined tensile bar-stirrup corrosion effect has been studied, the relative bond strength-corrosion curve of specimens with more stirrups lies below that of specimens with fewer stirrups, indicating further bond reduction of specimens with more stirrups.

To better understand how stirrups affect the bond strength, one may refer to Fig. 10 that compares the load increase for increased stirrups and the corresponding no-stirrup case in Moodi et al. [7]. As shown, when corrosion is increased, the bond strength is enhanced due to increased stirrups. In other words, specimens with 25% corrosion have the largest increase in the stirrup-induced bond strength; at this corrosion rate, the mentioned increase for 1, 2 and 3 stirrups in the spliced region is 68.7, 75.99 and 97.36%, respectively.

Although earlier studies have neglected to pay enough attention to high corrosion rates and some have even shown that stirrups do not affect the bond strength (of corroded bars), this study has shown that at high corrosion rates stirrups are more effective.



	S0	S1	S2	S3
C0	38.24	37.91	44.4	52.74
C2	34.63	42.7	46.74	54.7
C5	30.65	41.53	46.25	54.01
C10	28.89	38.27	42.41	47.37
C25	19.66	33.18	34.6	38.8

Fig. 8. Maximum bearing load.

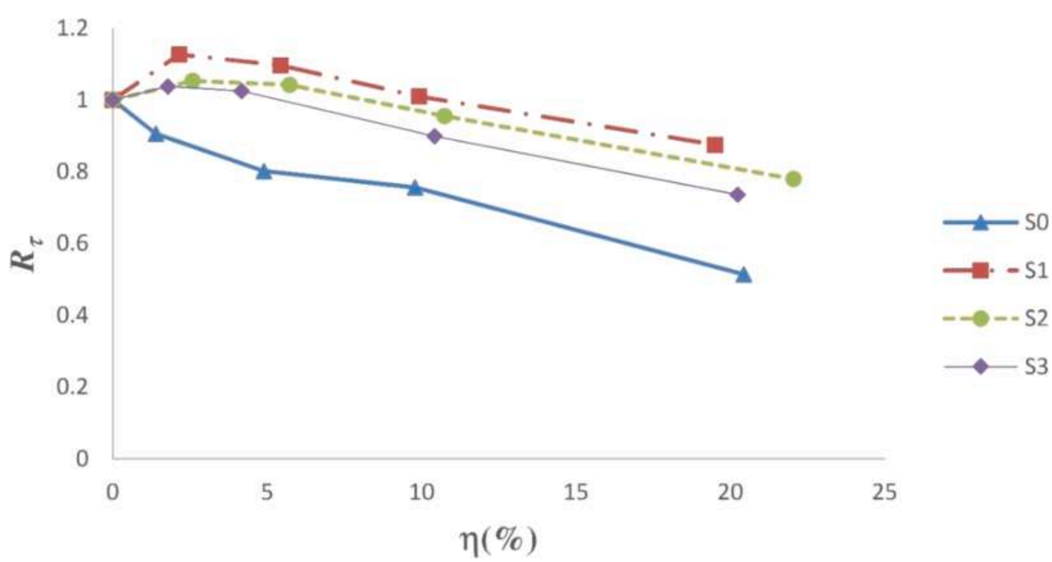


Fig. 9. Percent corrosion versus relative bond strength.

3.4. Energy dissipation and ductility

Ductility Index (μ) is considered as introduced in Cohn and Barlett [40]. It was calculated for all the specimens of this study (Fig. 11) and showed that the increased corrosion in specimens with 1 and 2 stirrups raise the ductility index. In specimens with 2 stirrups, this increase was less (almost equal for corroded ones), but in specimens with 3 stirrups, the increased corrosion reduced this index.

Load-displacement diagrams show that when stirrups are increased in the spliced region, the ductility index increases too. To better understand how corrosion affects μ, Fig. 12 compares it for two cases: one with 1, 2, and 3 stirrups (in the spliced region) and one with no stirrups (discussed in Moodi et al. [7]). The increase in μdue to the increase in stirrups is higher for 2 and 25% corrosion compared to other values (similar to the tensile bar corrosion in Moodi et al. [7]); thus, stirrups lead to more μ in high/low corrosion cases.

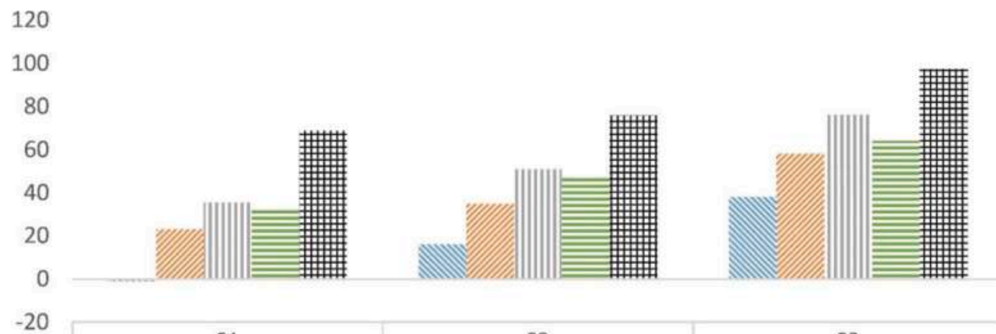
In Fig. 13, the whole area under the curve indicates the dissipated energy, the value of which is the highest when corrosion increases to 25% in specimens with 1 stirrup; at this rate, the energy dissipation is reduced in specimens that have 2 and 3 stirrups in the spliced region.

It is worth mentioning that when stirrups in the spliced region are increased, the energy dissipation is augmented too. This has been compared with the no-stirrup case (Moodi et al. [7]) in corresponding corrosions. Furthermore, the results (Fig. 14) have shown that stirrups increase the energy dissipation of specimens with corroded bars more than those without corrosion, and an increase in corrosion increases the energy dissipation due to increased stirrups; therefore, the highest stirrup-induced energy dissipation increase corresponds to the high corrosion (25%).

3.5. RSM for estimating relative bond strength of corroded bars

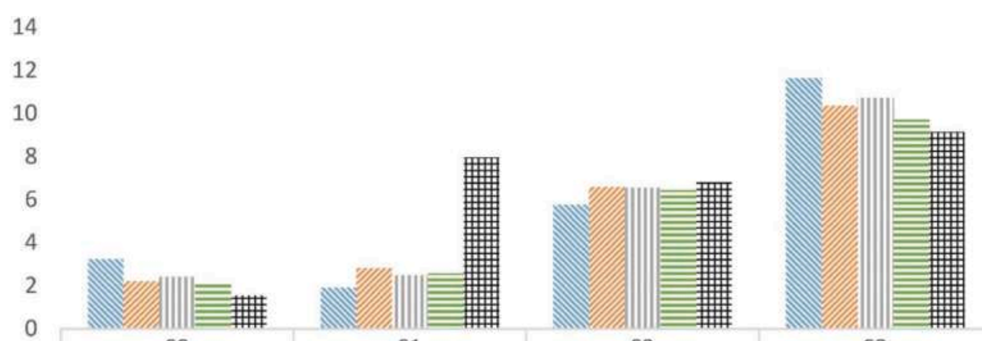
The RSM method has been adopted to provide a model for estimating the strength of the relative bond between concrete and corroded bars in lap spliced beam.

The main intention of RSM is to estimate a complex and real function with a simple and implicit function. Mathematically, each order of a polynomial in a Taylor expansion environs the selected random points



	S1	S2	S3
C0	-0.862970711	16.10878661	37.91841004
C2	23.30349408	34.96967947	57.95552989
C5	35.49755302	50.89722675	76.21533442
C10	32.467982	46.79820007	63.96677051
C25	68.76907426	75.99186165	97.35503561

Fig. 10. Load increase (%).



	S0	S1	S2	S3
C0	3.23	1.92	5.76	11.63
C2	2.19	2.83	6.59	10.36
C5	2.41	2.49	6.56	10.72
C10	2.19	2.57	6.43	9.71
C25	1.55	7.97	6.8	9.13

Fig. 11. Specimens' ductility index.

can be used to predict the appropriate response. Researchers have generally recommended the second order polynomial [41–42]. Hence, the second order of Taylor expansion is defined as follow:

$$f(X) = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \sum_{i=1}^{n} \beta_i X_i^2 + \sum_{i}^{n-1} \sum_{j=i+1}^{n} \beta_{ij} X_i X_j \quad (2)$$

where f(x) is the desire response, X is random variables and β is unknown coefficients. To determine the unknown coefficients, function may transform to the linear regression model. In other words, the second-order terms will change to the one-order terms as follows:

$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k + \varepsilon \quad (3)$$

where ε is the error. The above equation can be rewritten as:

$$y = \beta X + \varepsilon \quad (4)$$

The matrix coefficient is calculated using least squares approach as below:

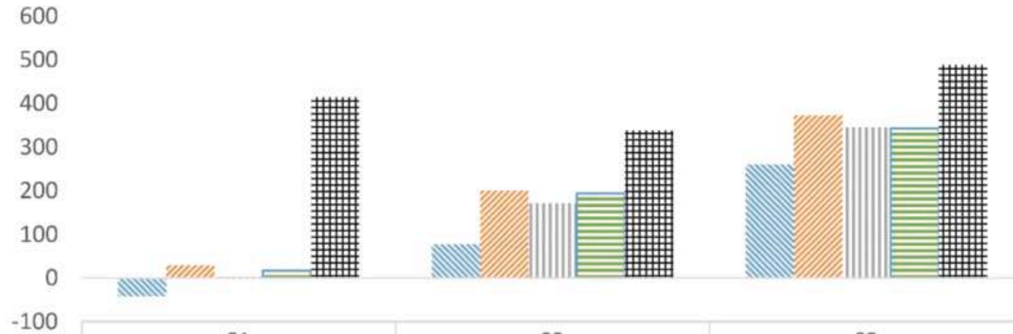
$$\beta = \left(\overline{X}X\right)^T X^T y \quad (5)$$

In this study, the relative bond strength is estimated by considering combined terms. In order to consider the stirrup distance (S_{st}) in relation to the relative bond strength, confinement effect of stirrups (k_{st}) is employed as presented in the Jiang et al. [43] study. k_{st} is calculated as follows:

$$k_{st} = \frac{A_{st}}{n S_{st} d_b} \quad (6)$$

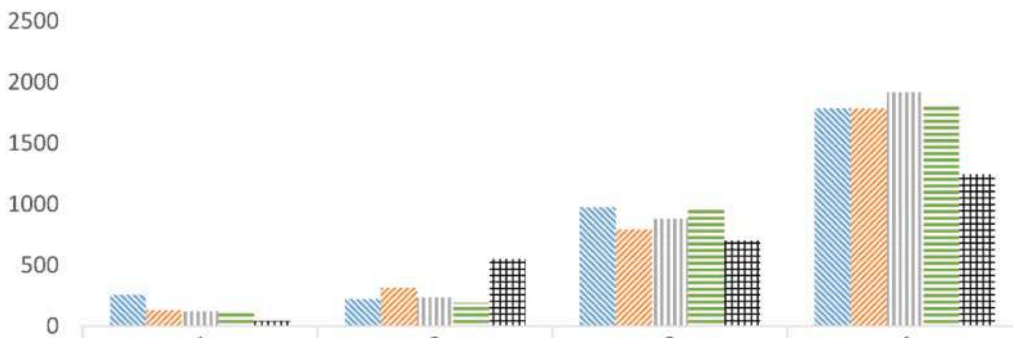
Where A_{st} is area of stirrups including all legs, n is number of tensile steel bars, and d_b is the diameter of longitudinal reinforcement. According to Orungun et al. [44] and Darwin et al. [45] studies, the distance of the stirrups in the spliced region is calculated by dividing the splice length (L_d) by the number of stirrups in the spliced region (N):

$$S_{st} = \frac{L_d}{N} \quad (7)$$



	S1	S2	S3
C0	-40.55727554	78.32817337	260.0619195
C2	29.22374429	200.913242	373.0593607
C5	3.319502075	172.1991701	344.813278
C10	17.35159817	193.6073059	343.3789954
C25	414.1935484	338.7096774	489.0322581

Fig. 12. Increase in ductility index (%).



	1	2	3	4
C0	257.47	221.37	979.53	1784.5
C2	133.73	318	793.35	1784.4
C5	124.49	235.4	881.12	1919.56
C10	113.4	191.21	979.64	1819.09
C25	45.82	553.61	702.47	1242.92

Fig. 13. Energy dissipation of beams.

By substituting Eq. (7) for Eq. (6), the coefficient k_{st} is calculated as follows:

$$k_{st} = \frac{NA_{st}}{nl_d d_b} \tag{8}$$

In order to provide a relation for estimating the relative bond via RSM, two parameters are considered as input variables including k_{st} and η, and the output is considered as R_τ. 17 specimens (out of 20 specimens) of this study were randomly selected for modelling and the remaining 3 specimens were used to evaluate the proposed model. A second-order polynomial was fitted to the output of experimental data based on input variables. The coefficients of this polynomial were calculated by subject to error minimum between the experimental and estimated data. Therefore, the relative bond strength relationship was obtained as follows:

$$R_\tau = 0.9060 - 0.0050\eta + 10.0446k_{st} - 0.000058\eta^2 + 0.0974k_{st}\eta - 138.185k_{st}^2 \tag{9}$$

In order to evaluate proposed model, a series of experimental data that does not influence the modelling process, is used. These experimental data include the remaining 3 specimens of this study and 6 specimens of Zamani et al. [47] study. The model performance is evaluated through such statistical indices as: 1) mean square error (MSE), 2) average absolute error (AAE), and 3) standard deviation (SD), provided in Moodi et al. [46] study. These indexes, calculated separately for modelling and evaluation specimens, are outlined in Table 2. Also, Fig. 15 shows the performance of the proposed model. These results indicate that the proposed model is in good agreement with experimental results.

4. Conclusions

This research tested 15 RC beams (with combined tensile bar-stirrup corrosion in the spliced region) under 3 different cases of corroded transverse rebars to study how the stirrup spacing affected the bond strength and concluded that:

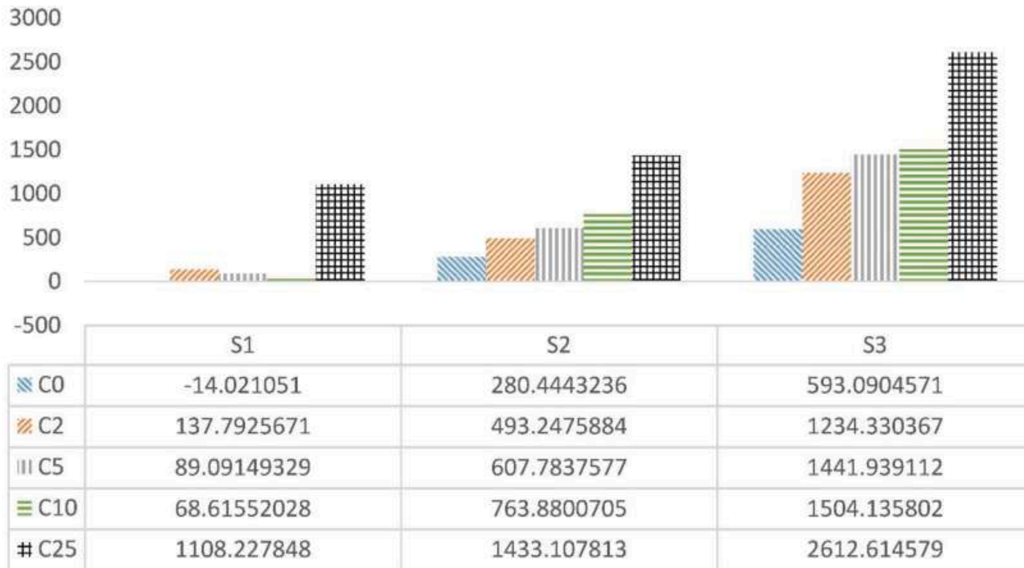


Fig. 14. Increase in energy dissipation (%).

Table 2
Statistical indicators for proposed model.

	MSE	AAE	SD
Proposed model for modelling data	0.328	4.563	5.88
Proposed model for evaluating data	0.464	5.57	6.94

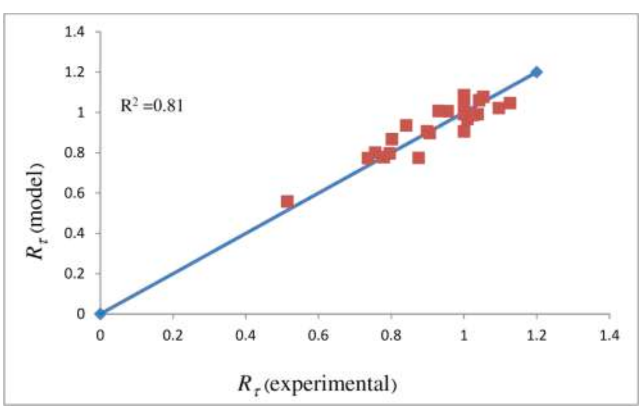


Fig. 15. Performance of model.

1. An increase in number of stirrups in the spliced region enhanced the bond strength, ductility index and the energy dissipation of lap-spliced beams with combined corrosion state.
2. For all three stirrup cases, the descending branch of the curve for relative bond strength versus corrosion had almost identical gradients: for 1, 2 and 3 stirrups, it was −0.0154, −0.016 and −0.017, respectively. However, the curve related to more stirrups lay below that of fewer stirrups.
3. At 25% corrosion, stirrups have the greatest effect on the enhancement of the bond strength, ductility index and the energy dissipation.
4. The model proposed by RSM for estimating relative bond strength is in good agreement with experimental results.
5. More corrosions increased energy dissipation due to larger number of stirrups.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.istruc.2021.03.096.

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