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A Comparative Study between the Analytical and Experimental Deflection Response of Corroded Simply Supported Reinforced Concrete Beams

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Abstract - This paper involves a comparative experimental and analytical investigation on the deflection behavior of corroded reinforced concrete simply supported beams. For this aim, two beams specimens of different dimensions are subjected to a lab-controlled environment to stimulate the effect of corrosion on their deflection values and two other beams of the same dimensions are kept intact as control beams. The impressed current technique is used for accelerating corrosion in beams for different periods of exposure. This has led to a different amount of corrosion in each beam. The load deflection variation of all the corroded and control beams is represented next when all beams are tested for bending until failure. On a parallel hand, an analytical attempt is run to determine the load deflection behavior using a simple mathematical modeling. The analytical approach involves the use of the modified deflection equations taking into account the amount of corrosion induced, the degradation in bond strength, and the resulting slippage effect in the beam. In both approaches, the corrosion phenomenon is shown to clearly affect the deflection behavior of the reinforced concrete beam. It is also noticed that a good agreement is achieved when identifying the analytical deflection value in simply supported reinforced concrete corroded beams in compare to the experimental acquired ones with some restrictions.

***Keywords*: *reinforced concrete – corrosion – deflection – bending test* - *analytical – experimental* -**

1. Introduction

The failure of a reinforced concrete structure can lead to loss of human casualties, loss of life, and collateral damage. Corrosion of steel reinforcement in structures is one of the reasons that may lead to failure phenomenon. Corrosion process leads to the formation of rust which overcomes the volume of steel up to six times depending on environmental conditions [1]. The volume increase of rust residuals activates cracking and spalling of the concrete, which can stimulus the mechanical performance and load capacity of the reinforced concrete (RC) structures [2]. For this aim, researchers and practitioners insist on continuous monitoring of the structure's health to contain any potential problem issuing from corrosion phenomena.

Nevertheless, the prediction of the behavior of corroded RC structures remains quite arguable. The use of the well-established and proven empirical equations of an un-corroded healthy RC element is considered unsatisfying when dealing with a corroded one. Some main modifications are needed in such case so that the effect of corrosion is sculpted in analytical investigation. Bichara and al. state that corrosion of RC beams decreases the reinforcing bar diameter and degrades the bond strength between steel and concrete causing slippage. This is believed to consequence a relatively main modification in the load-deflection capacity of the beam [3]. Others mention that corrosion of reinforcement may alter the failure mode for the corroded beam. The expected reduction in cross-section of the reinforcement has a major effect on the flexural capacity than on the shear capacity of a certain RC element. Zhu et al. agree on that and predict an added complexity for the available modelling strategy to evaluate the load-bearing capacity of corroded RC structures [4].

For this aim, a highlight on the validity of the available analytical tools to model the corrosion effect on beams is presented in this study. This is done by conducting a comparative analysis between both experimental and analytical methods of deriving the load-deflection behavior of simply supported reinforced concrete corroded beams.

At first, an experimental program is launched where 4 RC beams are casted and divided into two groups A and B. For group A, beams are of identical section where beam A0 is kept un-corroded and beam A1 is exposed to an impressed current to accelerate the corrosion process. As for Group B, a similar procedure is followed where beam B0 remains intact and beam B1 is subjected to an accelerated corrosion. After certain time, the exposed beams are discharged from the corrosion medium and a corresponding bending test is conducted. For each of the recorded applied point load, P_load, the mid span deflections of all beams are measured using an Linear Variable Differential Transformer (LVDT). On a parallel hand, an updated equation of deflection is employed in an analytical procedure to account for the corrosion induced, the degradation in bond strength, and the resulting slippage effect in the beam. For each recorded load , the corresponding deflection is obtained by the mean of the LVDT and the numerical equation as well. The load-deflection curves are derived for both approaches, analytical and experimental. At the end, a quantitative comparison is run to assess the validity of the analytical tool when compared to the experimental real deflection in simply supported reinforced concrete corroded beams.

2. Experimental Program

Natural corrosion formation takes relatively large time and needs specific environmental circumstances to be achieved. This makes it complex for researchers to study its effect on structural elements. Here comes the need to introduce manipulated experimental setups to achieve a kind of natural corrosion in reinforced concrete elements. Several methods exist, however the impressed current technique remains the most used and reliable. The justification for accelerating corrosion using an impressed current is strong where it dramatically reduces the corrosion initiation period from years to days and fixes the desired rate of corrosion without compromising the reality of the corrosion products formed [1].

However, it is noted in [2] that the characteristics of corrosion accelerated by impressed current differs from those of natural corrosion. This was profoundly studied by Yuan et al. in [3]. They have deduced that corrosion exists mainly on the surface facing the concrete cover in the artificial climate environment whereas it propagates uniformly on the whole surface of the steel bar when the impressed current technique is applied. Moreover, O'Flaherty et *al.* used an accelerated corrosion method to corrode many reinforced concrete beams of 910 mm in length with a cross section of 100 x 150 mm in [4]. Initially, the corrosion levels were calculated theoretically using Faraday's Law. (Eq.1)

$$M_{th} = \frac{W \times I_{app} \times T}{F} \tag{1}$$

where M_{th} is theoretical mass of rust (g), W is equivalent weight of steel (g), I_{app} is the applied current density (Amp/cm^2), T is duration of induced corrosion (sec), and F = Faraday's constant (96487 Amp-sec).

The actual corrosion levels found in the rebar when the process was over are shown to be different than the theoretical values derived from Faraday's Law. This is mostly attributed to the resistance provided by the concrete.

This situation was common in numerous studies [5], [6], [7], and [8]. In [9], H. Yalciner et *al*. piloted a full study on the flexural strength of concrete. They have grouped the beams into Group A and Group B. Four RC beams were tested in each group where the reinforcement patterns and the material characteristics differ. The accelerated corrosion method was implemented where a maximum of 16% corrosion level was reached indicating that 16% of the initial mass of the reinforcing steel bars have been dissolved due to the action of the galvanometric current. The actual corrosion level calculated in the exposed RC beams showed higher corrosion in stirrups than in main bars due to the low initial mass of the stirrups in compare to the longitudinal bars. In addition, the appearance of the cracks in the concrete and the loss in cross-sectional area of tensile reinforcing bars and stirrups all affected the bond strength and lead to a reduction in the capacities of corroded RC beams. As an example, the moment capacity of the same beam was reduced by 26% when like 8% corrosion was identified in its main tensile and transverse reinforcement.

Based on what is mentioned above, the impressed current technique is shown to be an effective and powerful tool to accelerate the corrosion process in a reinforced concrete beam. Therefore, a similar procedure is adopted in this study and run as described below.

2.1. Beams Casting

At first, it is worth to note that a large experimental program consisting of 16 reinforced concrete (RC) beam samples is conducted to investigate the behavior of the corroded RC line-like structures. In this study, four of these beams, denoted as A0, A1, B0, and B1 are only used. In table 1, the main features of the each of the beams are displayed.

Table 1: Initial properties of all beams

Beam Label	**A0 & A1**	**B0 & B1**
***f'_c* ***	28 MPa	21 MPa
***f_y* ***	550 MPa	550 MPa
Beam's Span *(L)*	2000 mm	500 mm
Beam's width *(b)*	200 mm	150 mm
Beam's depth *(h)*	250 mm	250 mm
Tensile Bars (Bottom)	2 No. 16	2 No.13
Compression Bars (Top)	2 No. 13	2 No.10
Shear Reinforcement	φ8 @10cm	φ6 @10cm

Note: f_c' is cubic compressive strength of concrete; f_y is yield tensile strength; Reinforcement bars are used as per the ACI designations for metric bars, * initial values before corrosion

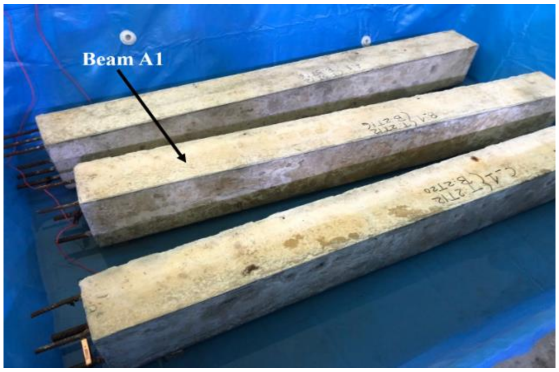

Figure 1: Beam A1 placed in water tank before current initiation

2.2. Impressed Current

Being casted, beams A0, A1, B0, and B1 are cured as per the ACI recommendations until reaching the design concrete compressive strength (28 MPa for beams A0 and A1, 21 MPa for beams B0 and B1). Then, the corrosion process is kicked off for the two groups of beams. A1 and B1 are moved and placed in two different water tanks along with other beam samples used for different research purposes. Inside, each of the beam is connected to a DC power source providing a current of 1.75A **at the beginning of the experiment**. The positive terminal of the DC power source is connected to the steel bars representing the anode and the negative terminal is connected to the counter electrode consisting of a stainless steel plate as cathode. The tank is filled with a 5% sodium chloride NaCl solution where the beam is partially immersed in the solution to the position of the tensile steel.

Figure 2: (a) Experimental setup of accelerated corrosion of reinforced concrete beams with B1 inside, (b) connection between beams, (c) power source providing DC current

Once the current is activated, the reinforcement bars inside the beams start to corrode and the solution colour is immediately altered to a darker rusty color. This is due to the lost steel ions propagating from all over the reinforcement under the effect of the chemical and electrical phenomena happening.

Figure 3: Experimental set-up where (a) A1 (b) B1 are placed at the end of current exposure

Beams A1 and B1 are disconnected from the DC power source at 2 different times: 9, 36 days respectively. A1 is kept under corrosion exposure for more time due to its larger section and heavier reinforcement. In figure 6, the effect of corrosion appears on B1 surface when compared to the control beam B0.

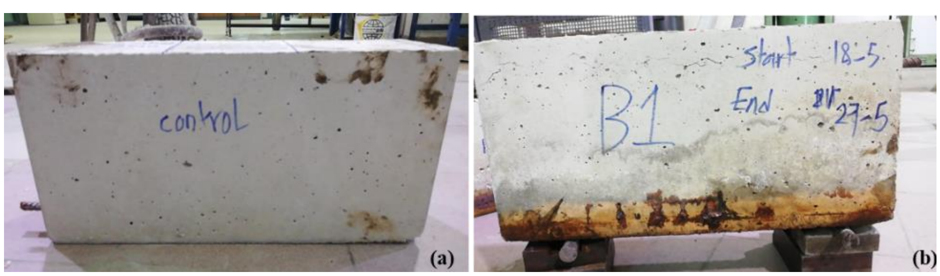

Figure 4: Beams (a) B0, (b) B1 after the corrosion exposure

2.3. Mechanical Test on Beams

The beams are mechanically tested using three-point loading and four-point loading test setups to assess their bending performance (see figure 5). Each beam is simply supported at both ends and loaded until rupture occurs. Below each beam, a Linear Variable Differential Transformer (LVDT) sensor with an accuracy of 0.01 mm is placed on the bottom part in the middle of the beam to record the mid-span deflection. The load deflection curve for each of the beams is then plotted.

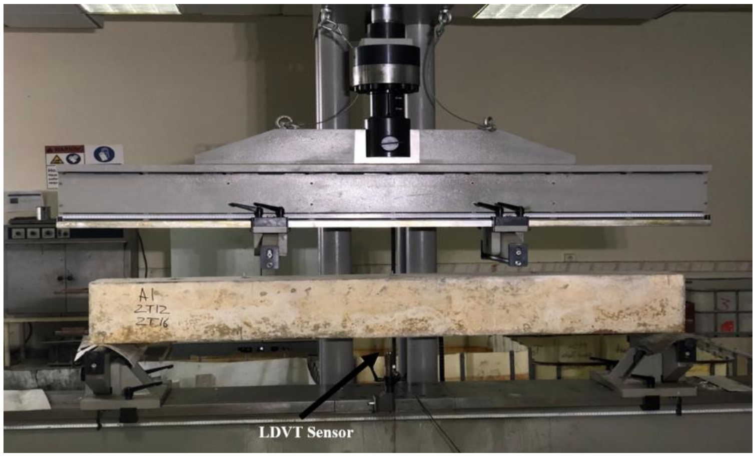

Figure 5: Four-point loading test performed on beam A1

2.4. Tensile test on corroded steel bars

Four pieces of steel bars are extracted from the tensile zones of A0, A1, B0, B1 beams. These bars are placed in a 2500-kN-capacity tensile machine at a loading rate of 0.5 kN/s. The ultimate and yield strengths of these bars are derived and employed in the analytical interpretation coming next.

2.5. Coring and testing of concrete sample

As known, a deficit in the concrete capacity is expected when corrosion activates throughout the beam's reinforcement. For this aim, coring test is conducted on each of the beam so that an accurate estimation of the residual compressive strength of existing concrete is derived. From each of the four beams, a 14cmx7cm cylinder is extracted and tested for compression in a later stage.

Figure 6: (a) Coring test performed on beam (b) Cores Extracted

2.6. Tensile steel extraction and cleaning

Further to the bending test, the percentage of mass loss in steel bars, Δ_w, is found for each of the corroded beams. This is done by extracting the tensile bars and performing a mechanical brushing and chemical cleaning procedures with a diluted hydrochloric acid solution, HCl. This allows an accurate prediction of the corrosion level when measuring the remaining bar diameter,d_{br}, in compare to the initially measured bar diameter, d_{b0}.

3. Analytical Investigation

Throughout history of reinforced concrete structures, deflection equations have been considered satisfactory in estimating the amount of displacement that may occur in a reinforced concrete beam for most of the common boundary conditions and loading types. However, this has not been reliable when one or many conditions of the structural element exhibit some modification. That's why, several efforts have been made by researchers to ease for practitioners the evaluation of the effect of corrosion on load deflection behavior of beams. Taking into consideration the loss of bar diameter, the variation of the bond strength, and the introduction of slippage effect led to a modified deflection equation for simply supported beams. Zhu et *al*. have first considered the percentage of mass loss in steel bars, Δ_w, which is related to the initial bar diameter d_0 and the residual bar diameter, d_r [10].

$$\Delta_w = \left(1 - \frac{{d_r}^2}{d_0^2}\right) \cdot 100 \tag{2}$$

Another factor that appear to affect the deflection is the bond strength degradation. Some attempts have been initiated to model this effect. Lee et *al*. succeeded in [11] to develop the following equation:

$$u_b = 5.21e^{-\boldsymbol{\Omega}\boldsymbol{\Delta}_{\boldsymbol{w}}} \tag{3}$$

where u_b is the remaining bond strength and Ω is a mathematical constant taken as -0.0561.

Next, the slippage effect can be estimated when the bond degradation amount is available. This has been an extensive topic of research for years. Yet, Yalciner et *al*. have proposed a simple equation in [12] where the amount of rotation settlement θ_s caused by the steel corrosion effect is found:

$$\theta_s = \frac{\varepsilon_s f_s d_b}{8u_b(d-c)} \quad for\ \varepsilon_s \le \varepsilon_y \tag{4}$$

$$\theta_s = \frac{d_b}{8u_b(d-c)}\left(\varepsilon_y f_y + 2(\varepsilon_s + \varepsilon_y)(f_s - f_y)\right) \quad for\ \varepsilon_s > \varepsilon_y \tag{5}$$

where d_b is the steel bar diameter, d is the effective depth of the beam, c is the depth of the neutral axis, ε_s is the steel strain, ε_y is the steel yield strain, f_s is the steel stress and f_y is the steel yield stress.

The above calculated parameters allowed a modification in the deflection equation of a simply supported beam point loaded at mid span by P_{load}. This beam is assumed to have a total deflection, d_t, based on [13]:

$$d_t = \frac{P_{load} * L^3}{48E_c I_e} + \frac{\theta_s L}{4} \tag{6}$$

where I_e is the effective moment of inertia of the structure, L is span length, and E_c is the concrete's modulus of elasticity. From all what is mentioned above, the deflection value for each of the load recorded during the bending tests performed on beams A0, A1, B0, and B1 is calculated as per Equation (6).

4. Results and Analysis

4.1. Actual Corrosion

As mentioned above, tensile steel bars embedded in the corroded beams are extracted and cleaned after the mechanical test. It is found that corrosion initiated is rather irregular with some corrosion pits existing on the steel bar. This makes it more complex to use the classical method to measure the residual diameter directly by a Vernier caliper. Linwen et *al*. calculated the mass loss of steel bar instead. In [2], they have determined the cross-sectional area loss to estimate the diameter loss. A similar procedure is followed in this study where samples of the extracted steel bars from beams A1 and B1 are weighed on a balance with an accuracy of 0.01 g and the cross-sectional loss is calculated using Equations 7 and 8.

$$\Delta A_s = \left(\frac{m_0 - m}{m_0}\right) \cdot A_s \tag{7}$$

$$m_0 = \rho \cdot A_s \cdot L \tag{8}$$

where ρ is the density of the steel bar, considered to be 7.85 g/cm^3; ΔA_s is the average loss of cross-section of the corroded bars, A_s is the nominal cross-section of the steel bars; m is the residual mass; m_0 is the nominal mass of the steel bars; and L is the length of the bar. In addition, the percentage of mass loss in steel bars, Δw, can be deduced when using equation 2. Table 2 summarizes all the values needed for the analytical investigation coming next.

Table 2: Estimated loss in steel due to corrosion

Rebar of beam:	L (cm)	m (g)	A_s (cm2)	m_0 (g)	ΔA_s (cm^2)	d_r (mm)	d_0 (mm)	Δw (%)
A1	76.2	1160	199	1190.36	5.08	15.71	15.9	**2.28**
B1	60	473	113	532.23	12.58	11.31	12.7	**20.68**

Note: A_s and d_0 are used as per the ACI Designations of Metric Bars, d_r is the residual diameter of bar calculated using the basic equation of the area of a circular cross-section by subtracting d_{lost} from d_r.

The results illustrated in table 2 shows that a severe corrosion attack hit beam B1 (20.68& corrosion level). Although there are similar experiment conditions in both beams and a shorter exposure time is set for beam B1, yet the smaller section dimensions and reinforcement diameter make B1 more vulnerable to the corrosion action initiated by the current. Thus a greater corrosion amount is found in B1 and heavier effect on the load deflection behavior is expected.

4.2. Material properties of corroded beams

Tensile strength tests are performed on a clean un-corroded steel specimen and the corroded steel bars extracted from beams A1 and B1. On the other hand, compression tests on removed concrete cores are conducted. The results shown in table 3 are next employed in the analytical estimation of deflection for all beams. A reasonable loss in both yield strengths of steel and compressive strength of concrete is witnessed.

Figure 7: Tensile test performed on extracted corroded steel

Table 3: Concrete and steel parameters after corrosion

BEAM	f'_c (MPa)	f_y (MPa)
A0	28	550
B0	21	550
A1	23.5	533
B1	12.1	497

4.3. Failure Mode

A common trend of failure is detected in all beams A0, A1, B0, and B1 as the load increases in the bending machine. Flexural and shear cracks start appearing throughout the span of the beams as shown in figure 8. However, shear failure occurs primarily due to the low shear capacity of the beam resulting from low transverse reinforcing. To be noted that more flexural and larger cracks have appeared in the corroded beams A1 and B1 (see figure 8). These cracks are formed in the middle zone of the beam and develop from the bottom (tensile surface) to the upper (compressive surface) with a faster rate of width increase. It is obvious that corrosion of tensile bars affects the behavior of failure of the beam. This was actually a main finding of Rodriguez *et al.* in their study of effect of corroded reinforcement on the load-carrying capacity of RC beams [14]. They proved that a shear failure is expected when corrosion attacks main and transverse reinforcement of beams. Similarly, Suffern et *al.* reported an increase of 53% for the possibility of a more severe shear failure for corroded RC beams [15].

Figure 8: Real vs. Processed images of beams A0 and A1 to show the crack pattern and failure mode

4.4 Load Deflection Curves

The load–deflection curves of the control beams (A0 and B0) and the two corroded beams (A1 and B1) are drawn after the bending tests are done. From figure 9, it is noticed that the ultimate load capacity of A0 is 134kN in compare to 154 kN when both beams are loaded until failure. A 12% increase in the load capacity of the corroded beam A1 is witnessed in compare to A0. This is not surprising since a low amount of corrosion is induced inside the beam, (2.3%), confirming what previous studies have shown. L. Berto et *al.* proved that a low level of corrosion leads to a minimal increase of bond strength in corroded RC beams resulting a higher beam load capacity [16]. In contrast, B0 has reached an ultimate load equivalent to 116kN. Yet, when more than 20% of corrosion level is detected in B1, the ultimate capacity has dropped to 72kN marking a reduction of 38% approximately when compared to B0. A similar finding is outlined in [17] were a higher corrosion level leads to a lower load capacity of the tested RC beam.

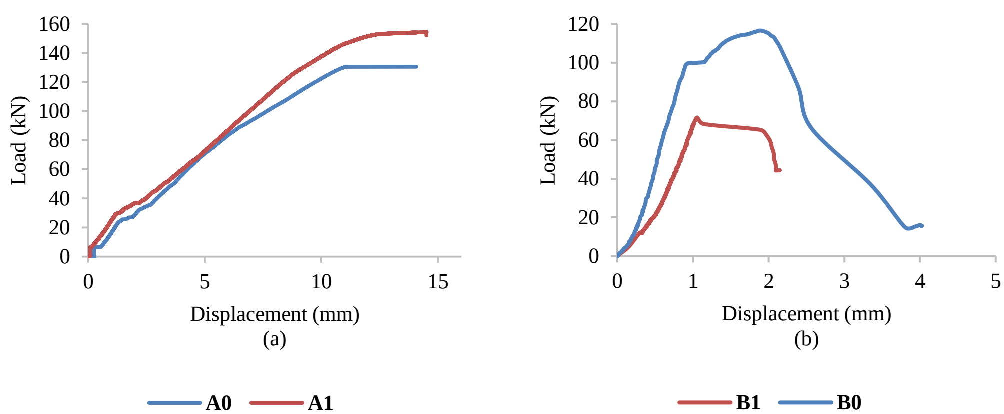

Figure 9: Load Deflection Curves of (a) Group A (b) Group B

4.5 Analytical Estimation vs. Experimental Estimation

In this study, the deflection values for control beams A0 and B0 are calculated using the basic deflection equation of a simply supported beam loaded by its self-weight and the recorded concentrated P_{load} applied at the midspan during the bending test (Eq.7). As for the corroded beams A1 and B1, the modified deflection equation, Eq.6, is used to assess the deflection values. Table 2 and 3 parameters are employed in the equation for the needed material properties.

$$d_t = \frac{P_{load} * L^3}{48 E_c I_e} + \frac{5\, w_{OW} * L^4}{48 E_c I_e} \quad (7)$$

where w_{OW} is the linear own weight load, I_e is the effective moment of inertia of the structure, L is span length, and E_c is the concrete's modulus of elasticity.

In figure 10, the deflection response for each beam is presented for both the analytical and experimental attempts. The values displayed below are extracted from the load-deflection coordinates recorded during the bending test in addition to the calculated values using equations 6 and 7. The comparison is limited to the loads applied over the beam just before reaching the ultimate value during the bending test.

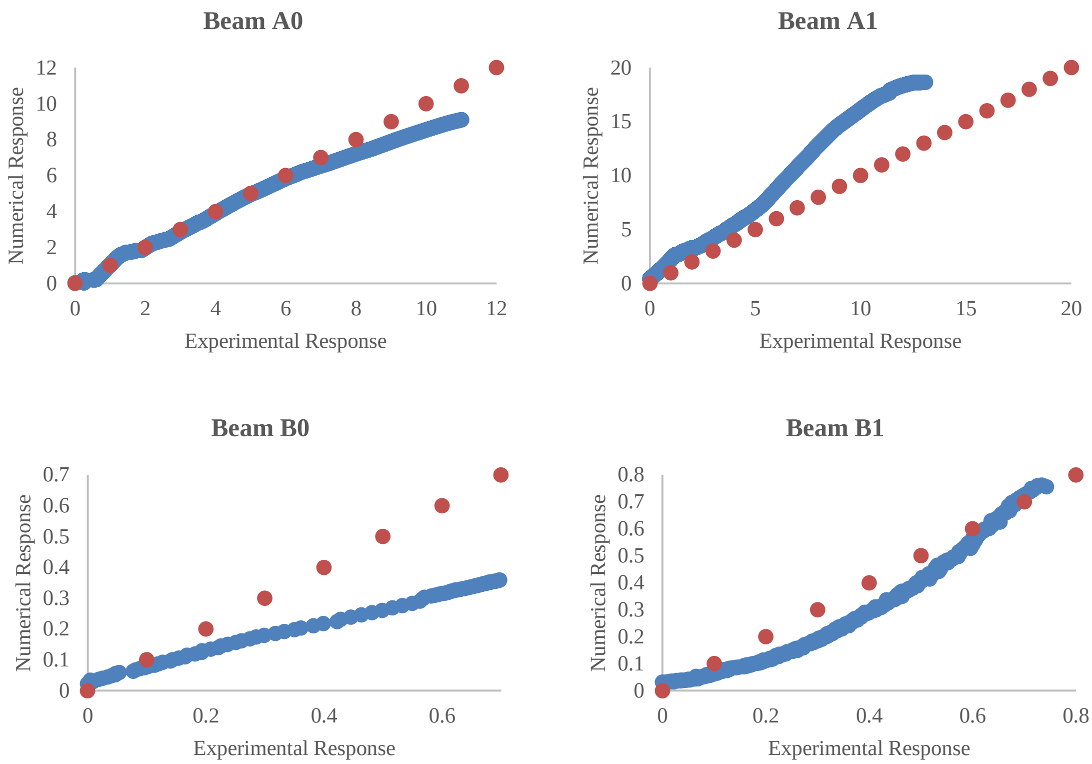

Figure 9: Comparison of the Experimental Deflection Values and the Analytical Deflection Values for beams: (a) A0 (b) A1 (c) B0 (d) B1

The comparative graphs displayed in figure 10 outlines many findings. At first, it is remarked that the basic deflection equation succeeded in estimating the real deflection values of uncorroded beam A0 (figure 10.a). When A0 is loaded with 58kN concentrated load at its mid span, the deflection value calculated with equation 7 is 4.17mm. This value is found to be close to the experimental one recorded by the LVDT sensor for the same loading (4.183mm). On average, a 6.8% difference between the analytical and experimental attempts is found. In their study, Sharma et *al.* reached a similar conclusion [18]. For beam B0 (figure 10.c), the experimental estimated values seem to be higher than the analytical calculated ones. On average, an 40% difference exists when comparing both approaches. As for the corroded beams, results of beam A1 deflection highlight promising finding. Although a moderate corrosion is hitting the reinforcement of A1, yet a fair amount of deflection values calculated using equation 6 converges relatively with the experimental values. When A1 is loaded by 26kN concentrated load at its midpsan, the anaytical evaluation leads to 5.49mm deflection in compare to 4.04mm experimental value. This is reflected in most of the considered point loads where the analytical estimated values are higher by an average of 38% than the real expected deflection values. Beam B1, affected by an average of 20% corrosion level, has behaved similarly to A1. The values extracted from the analytical interpretation are shown to be higher by 20% than those found in the experiment in B1.

5. Conclusion

Experimental and analytical investigations on the deflection response of simply supported reinforced concrete beams is reported in this study. Two different corroded beams are tested until failure by a convenient loading system. Another two similar beams of the same section but without corrosion are also tested as control ones. On a parallel hand, an analytical attempt is run where the deflection response of all the beams is estimated using the classical deflection equation and the modified one used for corroded elements.

1. The adopted impressed current technique succeeded in simulating small and large corrosion level in both beams A1 and B1, respectively.
2. The amount of corrosion induced in each of the beam has influenced many of the structural parameters of these elements: concrete compressive strength, steel yield strength, bar diameter, and reinforcement area.
3. All beams have witnessed an alteration in their load capacity based on the amount of the deflection induced. A small corrosion amount (less than 10%) has led to an increase in bond strength then in load capacity consequently.
4. The analytical method described has shown to be successful for most of the tested beams. For the uncorroded beam, a fair convergence in values is achieved for the assigned loading conditions. Yet, a slight difference is spotted in the corroded beam which is considered acceptable since the analytical values were higher than those evaluated in the experiment.
5. In group B beams, the results did not represent a perfect match. The analytical estimated deflections were smaller than the real values. This is mainly referred to the short span of the beam under testing and the complexity of reproducing the theoretical boundary conditions in such case.

The outlined results confirms the validity of the analytical procedure employed in this study. It consists of a simple calculation able to detect a reasonable deflection value, with certain limitations, for the corroded reinforced concrete beams. For future research, more case studies should be considered for different spans and corrosion levels.

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