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EVALUATION OF ULTRASONIC PULSE VELOCITY (UPV) FOR REINFORCED CONCRETE CORROSION

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This study was undertaken to evaluate the efficiency of the ultrasonic test for detecting reinforcement corrosion levels under varying conditions and to form a correlation between the ultrasonic pulse velocity (UPV) values and the flexural capacity of corroded beams. To establish this, several reinforced concrete beams were cast and subjected to an impressed current accelerated corrosion process. The severity of corrosion was then investigated using the UPV test and four-point loading test. The results showed that the UPV test values vary with the corrosion level of reinforcement in concrete beams. However, the degree of variation in UPV test values at different levels of corrosion does not permit a clear cut for the evaluation of corrosion severity, particularly at low levels of corrosion. The four-point testing of corroded beams showed that corrosion affects the flexural capacity and ductility of the beams. This effect was correlated in this study with the UPV test values. The correlation analysis showed that there exists a moderate to a high positive correlation between the UPV test values and flexural capacity of the beams while a low negative correlation between the UPV test values and ductility of the beams was observed.

Keywords: ultrasonic test, flexural capacity, corrosion, ductility

1 INTRODUCTION

Structural degradation due to corrosion of embedded reinforcement is still one of the major durability problems experienced by the construction industry [4, 6, 9, 15, 16]. Corrosion is triggered by either chloride Cl^- or CO_2 ion ingression through the concrete, reacting with and destroying cement hydration products that shield the embedded reinforcement. As corrosion initiates, the cross-section of reinforcement is reduced, thereby dropping its flexural and tensile capacities. This results in structural cracks on the reinforced concrete member, that is in turn, reduces its load capacity. In contrast to carbonation-induced corrosion, reports concluded that chloride-induced corrosion is more damaging and requires a higher cost to repair [17]. The ability to get measure the severity of corrosion in existing structures for inspection, maintenance, and scheduling and the use of inspection results for predicting the remaining service life is becoming progressively more important [1, 4, 6–8, 10, 11]. However, to date, no single inspection or monitoring method has been proven to be able to detect the whole corrosion process [3].

On the road to developing such a methodology, an ultrasonic approach for corrosion detection has been undertaken. This approach was selected owing to its relative feasibility for monitoring corrosion in reinforced concrete structures. Ultrasonic measurements can be utilized to detect internal defects and mechanical properties of concrete through the emission of elastic wave signals transmitted to concrete [7, 12–14]. When ultrasonic waves pass through concrete, the waves scatter, reflect, absorb, and diffract. Extracting the information from the signals and conducting inversion analysis, these data can be used to predict the mechanical properties and identify the distribution of defects in the material. A limited number of studies adopted ultrasonic testing to monitor the corrosion in concrete structures in a quantitative manner. Examples of such studies were performed by Yeih and Huang [14] that utilized ultrasonic testing for corrosion detection in concrete members and found that a correlation between the electrochemical properties of corrosion and the drop in ultrasonic amplitude can be established. Moreover, Xu and Jin [13] applied ultrasonic testing for corrosion monitoring of non-uniform surfaces of rebars. In their study, they also employed machine learning to develop models for corrosion level prediction. Other studies [3, 5, 9, 12] adopted guided ultrasonic waves for corrosion level detection in reinforced concrete members. Based on these studies, it was concluded that guided ultrasonic waves may have the potential to detect the entire corrosion process.

The reason for this limited use of ultrasonic tests for corrosion level detection in reinforced concrete members is that for full penetration of waves through concrete the excitation frequency of ultrasonic waves should be low (e.g., 500 kHz). However, the low frequency causes a longer wavelength, so a drop in resolution may take place [14]. This limitation requires further investigation on the accuracy of such tests in evaluating the corrosion level in reinforced concrete members. Therefore, this study was undertaken to evaluate the efficiency of ultrasonic testing for detecting reinforcement corrosion levels under varying conditions. Moreover, correlations between the loss in flexural capacity of reinforced concrete beams, corrosion level, and the drop in ultrasonic amplitude are established, thus, serving as an initial exploration toward the use of non-destructive tests for corrosion detection in reinforced concrete structures.

2 EXPERIMENTAL PROGRAM

This section describes the experimental program performed in this study. The experimental procedure comprises casting of reinforced concrete beams, demolding and curing of test specimens, subjecting test specimens to an accelerated corrosion process, and lastly evaluating concrete samples for corrosion severity using ultrasonic testing and a four-point bending flexural test. Figure 1 shows a schematic illustration of the experimental program.

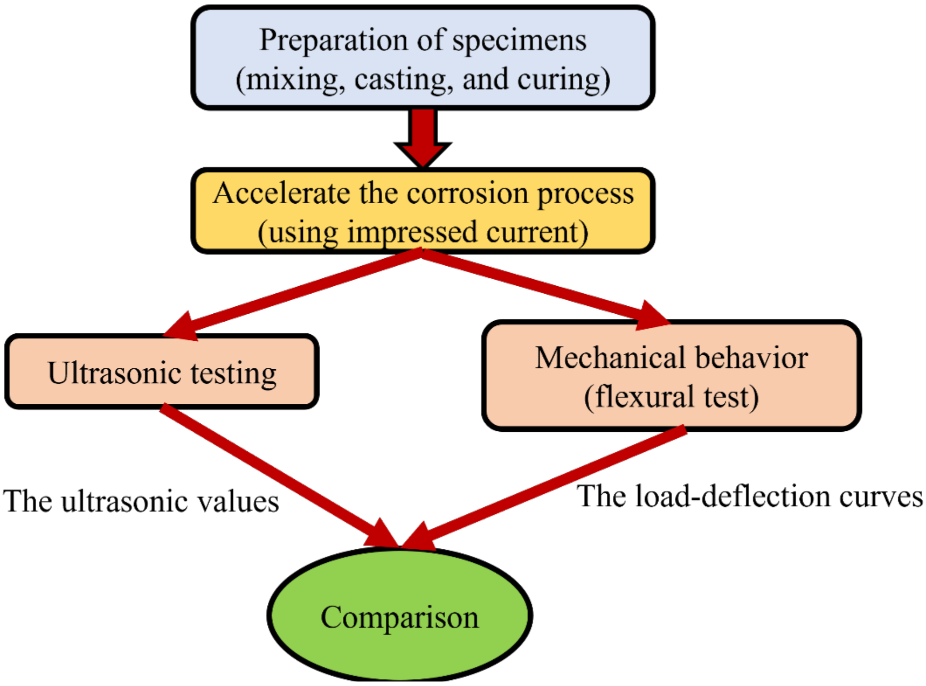


Fig.1. Schematic illustration of the experimental program for the evaluation of ultrasonic testing for corrosion detection

2.1 Test Specimens

Specimens of reinforced concrete beams were constructed per the ACI code [2]. Twelve beams with dimensions of 150×100×1000 mm were longitudinally reinforced with 2∅12 mm in the bottom and 2∅10 mm in the top, and a 6 mm stirrup that was placed at 50 mm intervals throughout the length of the beam. The general layout of the test specimens and reinforcement is depicted in Fig. 2.

Fig. 2. Beam reinforcement of the specimen

2.2 Material Properties

2.2.1 Concrete Mix

Following the concrete mix procedure in ACI-211, the concrete mix was constructed with a water-to-cement ratio of 0.47. Conventional Portland cement (Type I), coarse limestone aggregates (12.5 mm in size), silica sand, and crushed fine limestone combination (20 percent silica and 80 percent fine aggregate) were used in the concrete mix. Based on the ASTM standard method C127, the saturated surface dry (SSD) bulk specific gravity (BSG) and absorption of coarse limestone aggregate were determined to be 2.56 and 1.34 percent, respectively. Additionally, based on the ASTM standard method C128, the fine limestone aggregate had a bulk specific gravity (SSD) of 2.52 and absorption of 3.41 percent, respectively, and the comparable values for silica sand were 2.59 and 0.73 percent. Moreover, according to ASTM standard method C29, coarse aggregate has a unit weight of 1362 kg/m^3. Three concrete cylinders (100 × 200 mm) were made for each batch and tested for compressive strength, which was found to be around 41.6MPa for a w/c =0.47 mix.

2.2.2 Steel Reinforcement

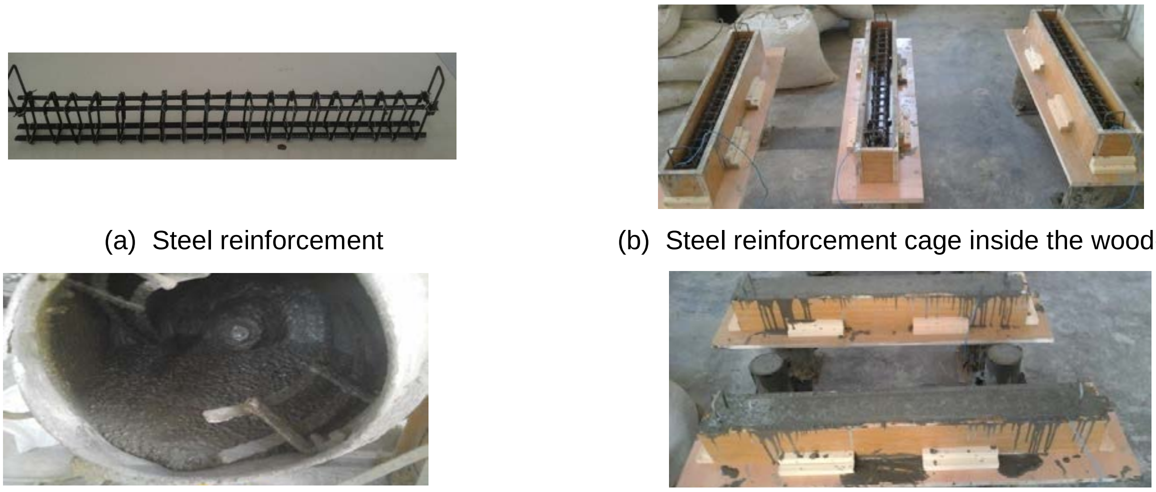
Two distinct grades of steel reinforcement were used to strengthen the beams: G40 and G60. Table 1 summarizes the mechanical properties of the steel reinforcement.

Table 1: Mechanical properties of steel reinforcement

Size	Grade	Yield Strength, Fy (MPa)	Ultimate Strength, F_u (MPa)	Elongation %
6mm	G40	290	353	14
10mm	G60	441.8	657	12.9
12mm	G60	435.5	631	14.7
14mm	G60	463	640	16

2.2.3 Casting of concrete beams

To cast the test specimens, internally dimensioned hardwood molds (100×150×1000 mm) were produced. Before casting the concrete, the steel reinforcement was constructed and set in cage-shaped molds. Each batch consisted of three beams and three cylinders (100×200 mm) cast in a tilting drum mixer with a batch capacity of roughly a quarter m^3. The slump was found to be around 50 mm by testing (per ASTM-C143). Three layers of new concrete were poured into the wooden molds, one on top of the other, each layer vibrating on the compacting table. After 24 hours, the beam specimens were demolded and wrapped in moist burlap for 28 days to cure. Figure 3 illustrates the construction phases.



(a) Steel reinforcement

(b) Steel reinforcement cage inside the wooden mold

(c) Mixing of concrete

(d) Casted specimens

Fig. 3. Mixing, casting, and curing of beams

2.3 Corrosion process

Impressed by electricity, the corrosion process on the reinforced concrete beams was accelerated using DC current. The rapid corrosion process was done by passing DC (direct current) through metallic wires placed before casting to both the longitudinal steel bars and stirrups, which function as anodes within each beam. A steel plate with dimensions of (800×300×10 mm) was used to make the cathode, which was connected to the cathode wire. A current density of 200 A/cm^2 was applied to the specimens. To establish an aggressive environment, samples were placed in a tank containing a 2% NaCl solution. Figure 4 illustrates the processing phases.

(a) General overview

(b) Connecting the anode and cathode with the device

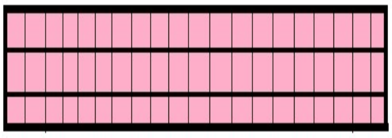
(c) After three days

(d) After eight days

Fig. 4. Accelerated corrosion procedure

2.4 Ultrasonic Pulse Velocity (UPV)

Nondestructive tests are used to determine the physical properties of concrete, such as discontinuities and changes in the material composition and degree of corrosion, without damaging the samples, allowing them to be reused following the test. The UPV was performed directly on two opposite sides of the beam separated by 10 cm. On the two sides of each beam, a square cell grid of 5 cm width was drawn to assist the UPV measurements. The UPV determines the speed at which the ultrasonic pulse travels between two opposing sides of the reinforced concrete beam. Three successive UPV measurements were taken (before corrosion, after 3 and 8 days of corrosion). Each beam was subjected to 60 UPV measurements in total for each case. Figure 5 illustrates the UPV measuring process.



(a) Test region segmentation

(b) After test

(c) Ultrasonic pulse velocity apparatus used

Fig. 5. UPV measuring process

2.5 Flexural behavior

Flexural testing was performed on the beams with four-point loads across a 0.9 m span using a basic support setup. A 300 mm space remained between the two loading locations. The beam was supported by a particular type of hardened steel support to ensure that no deformation occurred that might affect the test results. All beams were loaded with two-point loads at a loading rate of 0.3 kN/sec using 400 kN hydraulic testing equipment. On one end, the supports operate as a hinge, while on the other, they function as a roller. A linear variable displacement transducer (LVDT) was used to determine the vertical deflection at the mid-span. Load-deflection curves were developed using load cell and LVDT data. The test setup is depicted in Fig. 6.

Fig. 6. Four-point flexural test setup

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Beam failure mode

With four-point loads, all beams were tested in flexure. As the load increased, the beams developed flexural cracks in the high moment zone area, which spread into the compression zone and propagated over the shear span. Before collapsing, the fractures extended deeply into the compression zone, and the reinforced concrete beams ultimately failed because of steel reinforcement failure followed by compression zone crushing.

3.2 Mechanical behavior of RC beams

This section presents and examines the mechanical response and characteristics of different beams with and without corrosion degradation. The mechanical properties of the beams were determined using load-deflection curves and their associated characteristics, including maximum displacement, maximum load, initial stiffness, and toughness. Figure 7 illustrates the influence of corrosion on the mechanical behavior of reinforced concrete beams using load-deflection curves. The average characteristics of the curves have been established and are given in Table 2. From the results, it was observed that the curves first demonstrated linear behavior before developing nonlinear characteristics and all corroded beams had a lower load capacity than uncorroded beams. In addition, the average residual load capacity of all corroded beams is lower than the capacity of the control beams. Moreover, it was observed that the ductility and initial stiffness of the corroded beams is higher than the corresponding uncorroded beams (compare the maximum deflection of corroded and uncorroded beams in Table 2) and the toughness (defined by the area under the load-deflection curve) is decreased with corrosion.

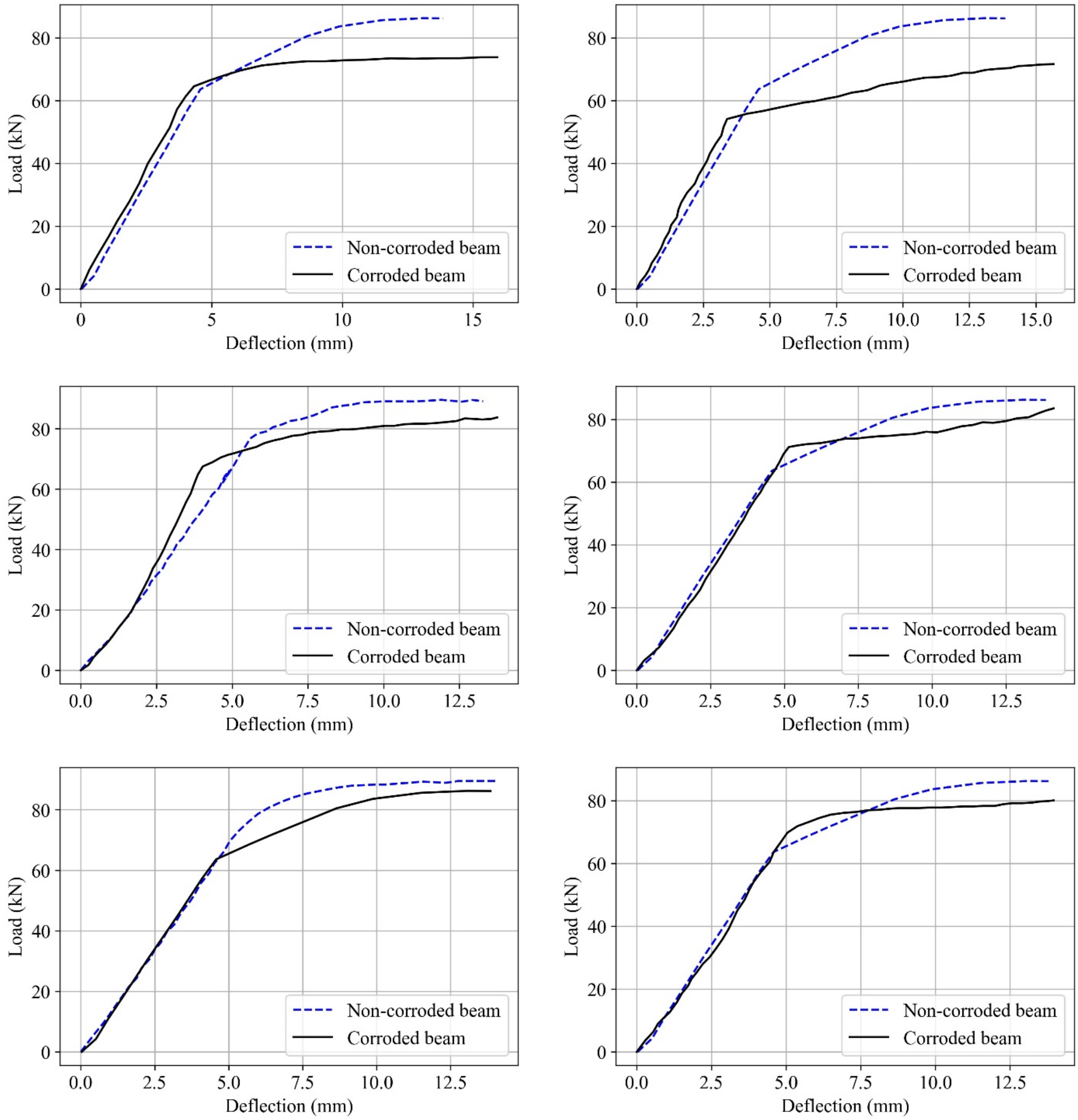


Fig. 7. Load-deflection curves for different corroded beams and their corresponding uncorroded ones.

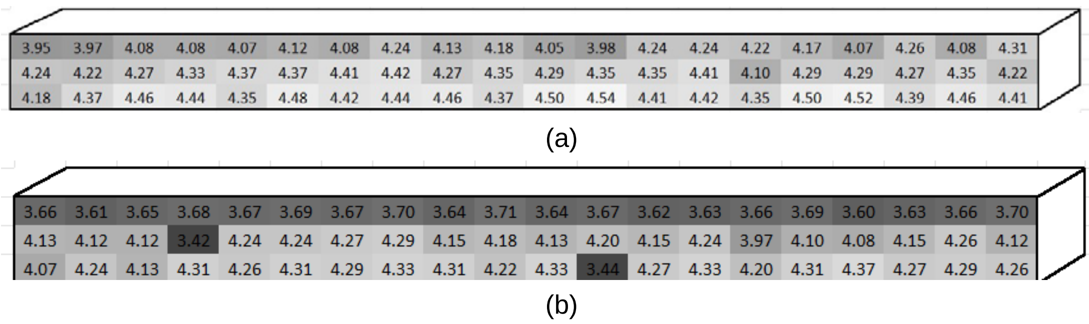
Table 2. Average mechanical characteristics for control and corroded beams (8 days of accelerated corrosion)

Beam Designation	Ultimate Load (kN)	Max Deflection (mm)	Toughness (J)	Stiffness (MN/m)
Corroded beams	72.7 (84%)*	15.80 (114%)*	928.0 (106%)*	15.21 (111%)*
Control beams	86.2 (100%)*	13.9 (100%)*	877.5 (100%)*	13.75 (100%)*

*Residual properties

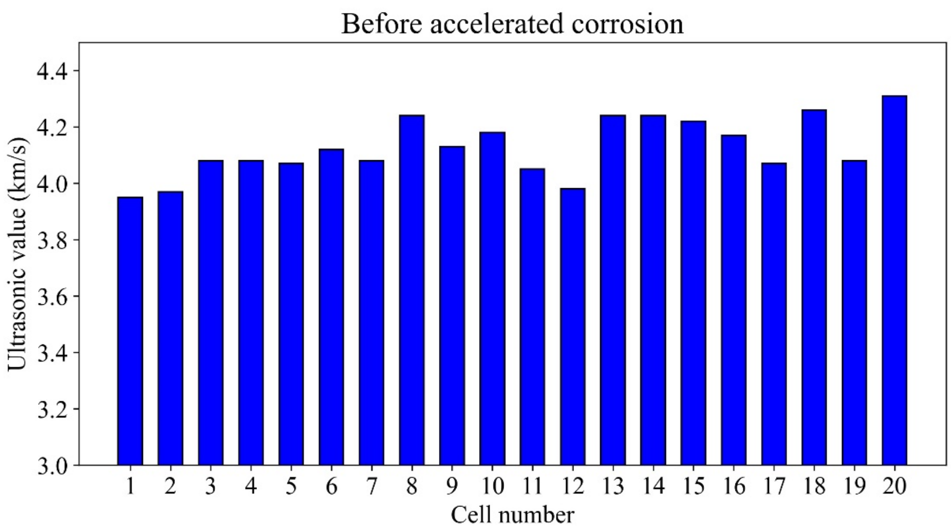
3.3 Ultrasonic Pulse Velocity (UPV)

Performing the UPV test at different levels of corrosion results in the measurements illustrated in Fig. 8 and Fig. 9 for one of the tested beams. As shown from these figures, the variation of measurements within the beam for a certain level of corrosion is not significant (the largest standard deviation of measurements was 0.105). Thus, in the case of uniform corrosion, the fine segmentation of the test region is not necessary. This reflects the good repeatability and reliability of the UPV test. However, it should be noted that this repeatability and reliability of measurements may also depend on the apparatus used not just the nature of the test. Therefore, verifying the reliability of the apparatus may be needed before the test. The figures also show that the UPV test values reduce as the level of corrosion increases. However, the reduction may not permit well-defined margins between the different levels of corrosion. For example, comparing the middle row of measurements in Fig. 8a and Fig. 8b will observe indistinct interfaces of UPV measurement between the different levels of corrosion.



(c)

Fig. 8. UPV measurements for one of the tested beams at different levels of corrosion (a) before corrosion, (b) after 3 days of accelerated corrosion, and (c) after 8 days of accelerated corrosion. The color intensity indicates the relative value of each UPV test value with dark colors representing low relative value.



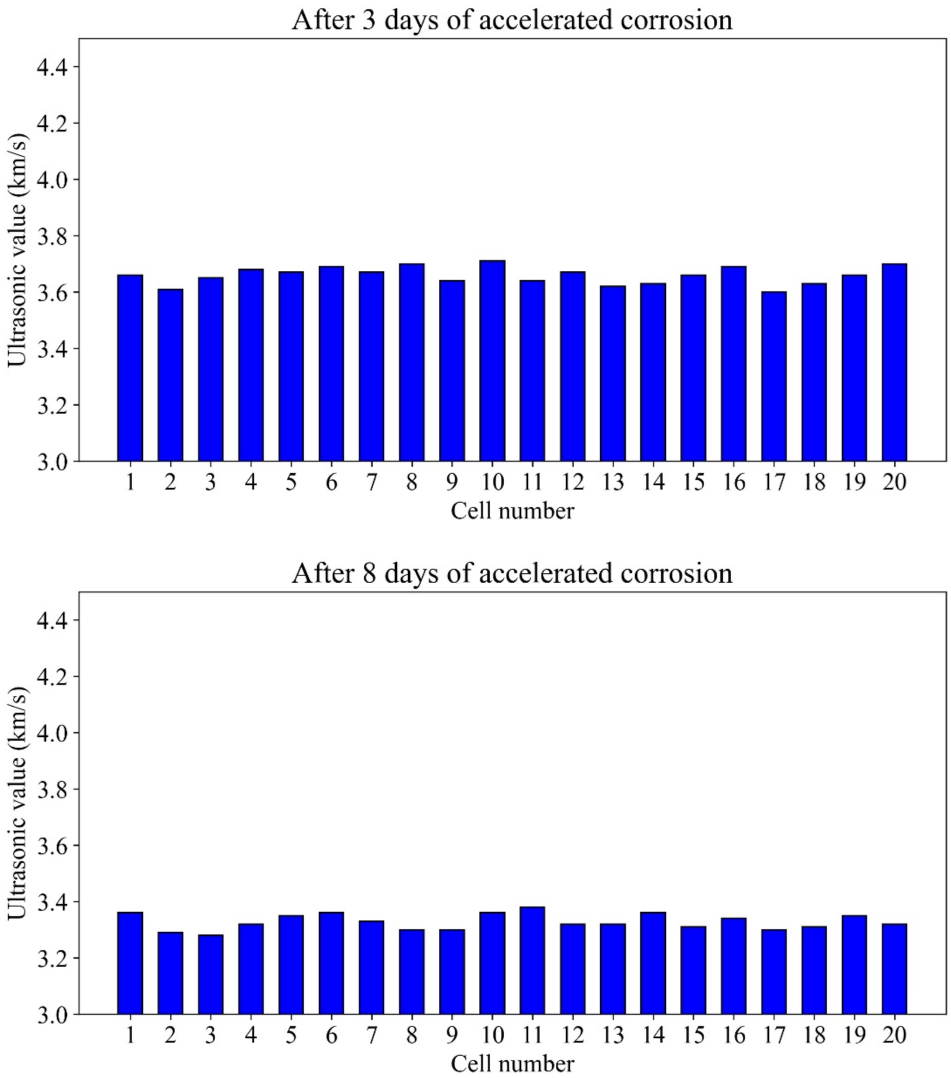


Fig. 9. UPV values versus the cell number for one of the tested beams at different levels of corrosion

3.4 Correlation between UPV test and four-point loading test

Conducting a correlation analysis between the UPV test and four-point loading test results in a positive correlation between the UPV values and the flexural capacities of the corroded beams and a negative correlation between the UPV values and the ductility of the corroded beams. A Pearson's correlation coefficient of 0.73 indicated a moderate to a high correlation between the UPV values and flexural capacities of the beams while a Pearson's correlation coefficient of -0.52 between the UPV values and ductility of the beams suggested a low negative correlation between the results.

4 CONCLUSION

The following conclusions can be drawn:

- Corrosion of reinforcement embedded in concrete members affect the flexural behavior of reinforced concrete beams by decreasing their flexural capacity and increasing their toughness, stiffness, and ductility.
- UPV test values reduce with the increase in the level of corrosion. This reduction does not offer distinct margins between different levels of corrosion.
- It was observed with a reliable UPV apparatus, fine segmentation of the test region is not necessary as the variation of UPV measurements within the beam is not significant.
- A correlation analysis between the UPV test and four-point loading test indicates a high to a moderate positive correlation between the UPV values and flexural capacity of the corroded beams and a low correlation between the UPV values and ductility of the beams.

5 ACKNOWLEDGEMENT

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