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ORIGINAL RESEARCH
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*Corresponding author. Laboratory of
Civil Engineering and Environment,
High School of Technology of Sale,
Mohammed V University in Rabat,
Morocco.
E-mail: ouadie.mouhat@gmail.com



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Non-destructive evaluation of steel rebars corrosion in concrete beams

Fatima Elmennaouy and Ouadia Mouhat* 

Laboratory of Civil Engineering and Environment, Mohammadia Engineering School, Mohammed V
University in Rabat, Morocco

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ABSTRACT

The present study aims at developing a non-destructive evaluation technique based on elastic wave scattering and the finite element method for the detection and evaluation of localized damage in rebar of reinforced concrete beams. Simulation of corrosion effect was taken for a tensile bar by creating a defect in this bar while the rest of the rebar and stirrups were kept unchanged. The study is based on comparison of propagation pattern of elastic waves in the presence and in the absence of defect. The proposed method was found capable to provide non-destructive evaluation of rebar corrosion in reinforced concrete beams, thus enabling diagnosis of reinforcement concretes structures attacked by corrosion. The obtained results can be further used to locate corroded areas.

KEYWORDS

detection, corrosion, rebar, concrete, non-destructive evaluation, finite element method

1. INTRODUCTION

Reinforced Concrete (RC) is a material characterized by durability and long life in very harsh environmental conditions and corrosion cracking is a main penalty in terms of safety and reliability for the various fields of manufacturing and industrial in particular civil engineering [1]. Acoustic non-destructive assessment of rebar corrosion is a hazard can suddenly cause a rather dramatic catastrophic failure especially for reinforced concrete structures, a proposed non-destructive rebar characterization methodology [2]. Damage detection in composite floor beams by the acoustic emission method show that fracture shape failure develop [3]. Corrosion is one of the main forms of attack caused by the environment that affects RC structures [4]. This deterioration is usually induced by chemical degradation of the cementation matrix, which reduces protection of rebar, which then suffer corrosion [5].

To ensure durability of RC constructions, rebar corrosion inspection is required. There are two types of rebar corrosion testing techniques: Destructive Testing (DT) and Non-Destructive Testing (NDT). DT based methods provide straightforward and accurate information, but execution speed and extension of examined areas should be restricted. In addition, this way of testing causes local damage to RC structures. On the opposite, NDT based methods do not harm inspected parts and have a faster testing speed and a bigger testing coverage than DT. However, they may show only a limited testing accuracy if they are not adequately executed.

As a result, NDT techniques can be judged to provide a better option for state monitoring of RC structures evaluation if accuracy issue is assessed [6, 7]. Recently, the use of the guided elastic waves has become a popular method for non-destructive testing of structures. Ultrasonic Guided Waves (UGW) have been found to be highly sensitive to most types of damage and efficient in detecting small and deep defects [8]. In light of the many wave modes propagating in concrete and along an embedded rebar, guided wave application for assessing the structural integrity of concrete structures have recently been described to enable detecting of defects in concrete and reinforcing rebar [5].

R. R. Hussain [7] have shown that ultrasonic guided waves can be used to determine the existence, position, and dimensions of surface rust. Q. Tang et al. [8] proposed two corrosion indicators, baseline and center frequency to detect and quantify corrosion in a cylindrical rebar. Q. Tang et al. [9] used a Wave Finite Element Method (WFEM) to study the propagation of ultrasounds in a damaged steel reinforced beam. This enabled to estimate the amplitudes of right and left propagating waves at near-zero wave number. The ratio of these wave amplitudes is reduced as a result of localized damage. A sensor array that is placed on one side of the potential damage site can be used to sense this ratio in practice in order to localize damage zones.

Sriramadasu et al. [10] have used UGW scattering to perform detection and evaluation of corrosion in naked rebar. They used the arrival time of dominant modes to fix the limits of the damaged zone. They introduced a scatter coefficient that enables to characterize dispersion of energy in corroded rebar. They demonstrated that this coefficient undergoes a perceptible increase as mass of steel is lost by corrosion. Mustapha et al. [11] have used the wavelet transform to localize delamination damage in RC structures.

The present study aims at developing a NDT technique which is based on the Finite Element Method (FEM) and scattering of UGW in order to make detection and evaluation of localized damage in the reinforcements of RC beams. A study regarding the behavior of Lamb waves, in terms of change of amplitude, due to the presence of a corrosion defect in a steel beam is performed. Simulation of corrosion effect is realized for a tensile bar, while the stirrups and the rest of the structure remain unchanged. The detection procedure relays on comparing the behavior of the wave signal in the damaged beam (with corroded rebar) and that in the intact beam (without corrosion). This allows quantifying amplitude change caused by corrosion in the tensile rebar. As a final stage, localization of the corroded zone and the extent of corrosion can be used to conduct reanalysis of the structure, and to calculate the modified displacements and stresses in RC elements as affected by corrosion.

Several studies have been conducted to study the phenomenon of corrosion by fixing the sensors to the ends of reinforcement [12, 13].

2. GUIDED WAVE PROPAGATION IN ELASTIC STRUCTURES

Lamb waves are elastic waves propagating in solid media, the wave propagation model used in this work is that presented in [14]. The Navier governing equation of wave propagation is given by:

$$(\lambda + G)\nabla\nabla\cdot U_i + G\nabla^2 U_i + \rho f_i = \rho \ddot{U}_i, \quad (i = 1, 2, 3), \quad (1)$$

where U_i is the displacement along the x_i axis; f_i is the body force component along the x_i axis; ρ is the density; G is shear modulus; $\ddot{U}_i$ is the acceleration; λ is Lamé constant; ∇ denotes the nabla operator and the double dot designates second partial time derivative,

$$\lambda = \frac{2\mu\nu}{1-2\nu}. \quad (2)$$

The solution to the governing Eq. (1) will be present in following form:

$$\begin{aligned} U_1 &= A_1 \cos(m\theta) e^{i(kz - \omega t)}, \\ U_2 &= A_2 \cos(m\theta) e^{i(kz - \omega t)}, \\ U_3 &= A_3 \cos(m\theta) e^{i(kz - \omega t)}. \end{aligned} \quad (3)$$

Using the Helmholtz decomposition [15, 16], Eq. (1) represents in a simple form exhibiting two parts than can be grouped as

$$\nabla \left[(\lambda + 2G)\nabla^2 \varphi - \rho \frac{\partial^2 \varphi}{\partial t^2} \right] + \nabla \times \left[G\nabla^2 \psi - \rho \frac{\partial^2 \psi}{\partial t^2} \right] = 0, \quad (4)$$

where φ and ψ are the scalar and vector potentials and $\nabla \times$ denotes the curl operator, ∇^2 the vector Laplacian and t is time. These potentials are not unique. Fixing the uniqueness condition of the potentials by imposing the two terms between brackets in Eq. (4) to vanish, one obtains the equations:

$$\frac{\partial^2 \varphi}{\partial x_1^2} + \frac{\partial^2 \varphi}{\partial x_2^2} + \frac{\partial^2 \varphi}{\partial x_3^2} = \frac{1}{c_L^2} \frac{\partial^2 \varphi}{\partial t^2}, \quad (5)$$

and

$$\nabla^2 \psi = \frac{1}{c_S^2} \frac{\partial^2 \psi}{\partial t^2}, \quad (6)$$

with

$$c_L^2 = \frac{\lambda + 2G}{\rho}, \quad c_S^2 = \frac{G}{\rho}. \quad (7)$$

Being the longitudinal and transverse (shear) volumetric wave velocities, respectively.

Equations (5) and (6) represent all the possible elementary volume waves that can propagate in the elastic medium: dilatation of shear waves. The process of resolution should also consider the boundary conditions. These can yield existence of special waves as particular solutions that combine both of these two elementary waves, functioning as surface Rayleigh waves or Lamb waves, or in general what is called guided waves. Analytical solutions exist for some specific domain geometries and boundary conditions. In the following, numerical modeling is considered in order to capture in a more general form guided waves in RC structures.

3. NUMERICAL MODELING OF RC BEAMS

Finite element modeling of elastic wave propagation occurring in a finite RC beam is considered in this section.

3.1. Beam geometry and material properties

The RC beam is assumed to have a constant rectangular cross section. The beam length is $L_b = 3.30$ m, the width of the cross section is $W_b = 0.20$ m and its height is $D_b = 0.30$ m.



Table 1. Mechanical properties of RC beam materials

Material	ρ (kg m ⁻³)	λ (GPa)	G (GPa)
Concrete	2,500	4.658	10.87
Steel	7,850	115.4	56.92

The material properties of the RC beam are given in Table 1.

The beam is reinforced in the upper part of the section with two compression bars having a diameter of 12×10^{-3} m, and in the lower part of the section with two tension bars having a diameter of 14×10^{-3} m. Stirrups with a diameter of 6×10^{-3} m and a spacing of 10×10^{-2} m compose the shear reinforcements. For concrete protection of the reinforcement, a cover of 25×10^{-3} m is used. Table 2 summarizes the diameters and surfaces of the bars used in the RC beam. Figure 1 gives details of the rebar and stirrups. Figure 2 shows location of the defect in the reinforcement beam.

3.2. The method of detecting corrosion defects for a reinforced concrete beam

The fault detection method in a concrete beam with steel reinforcements along the x axis is cut in two phases, the first in a holy beam before the application of the fault and the second with a beam of the same geometric characteristic but damaged; the two specimens are it is shown in Fig. 3, with a 5-cycle tone. $A(t)$ cycles applied to the sensor at end A, regenerating a Lamb wave signal that is picked up by the sensor. Side B is $B(t)$ [17].

The wave captured normally is reversed in time as $A'(t) = B(-t)$ then the application again on the side of B' which is normally a test tube in holy reinforced concrete.

Table 2. Diameters and surfaces of the bars used in the beam

	Diameter ($\times 10^{-3}$ m)	Area ($\times 10^{-5}$ m ²)
Stirrup	6	2.8247
Compressive rebar	12	11.3100
Tensile rebar	14	15.3930

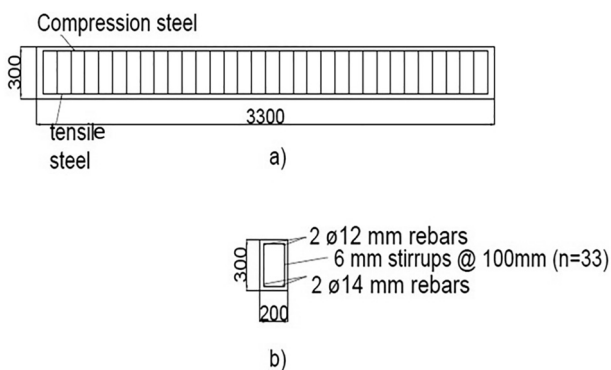


Fig. 1. Details of reinforcements of the RC beam; a) longitudinal section view showing the longitudinal bars and stirrups spacing; b) cross-sectional view showing a stirrup bar (all dimensions in $\times 10^{-3}$ m) (Source: Author)

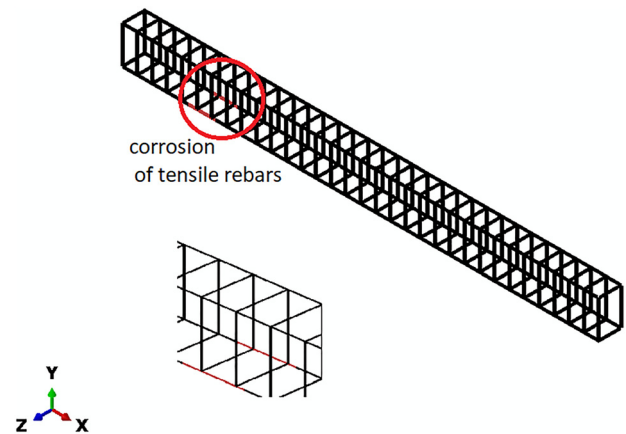


Fig. 2. Location of corrosion in the beam (Source: Author)



Fig. 3. Steel time reversal detecting system (Source: Author)

3.3. Boundary conditions

The beam is assumed to be pinned $U_1 = U_2 = U_3 = 0$ at the section position $x = 0.825$ and position $x = 2.475$. Figure 4 shows the boundary conditions imposed to the RC beam motion.

3.4. Analysis results

Simulations were carried out by means of ABAQUS/Explicit Finite Element (FE) software packages. The C3D8 (3D 8-node linear isoperimetric element) was used for meshing. A uniform mesh with cubic elements was created for six different mesh sizes. The mesh size was gradually increased from 10 mm up to 60 mm. Figure 5 shows the convergence analysis between stress and mesh size used for the RC structure.

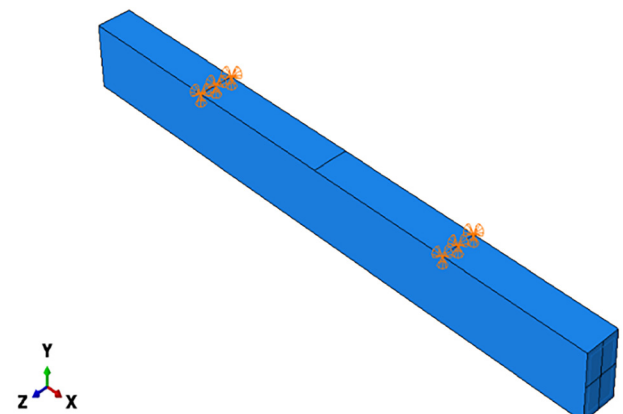


Fig. 4. Boundary conditions considered for the RC beam (Source: Author)

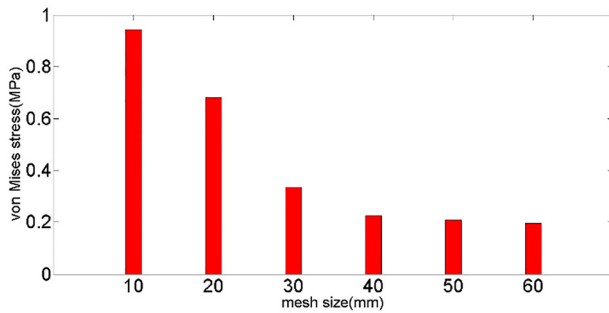


Fig. 5. The study of the mesh convergence on von Mises stress values for six mesh size elements (Source: Author)

The choice of mesh fineness is an essential issue in finite element simulations: the finer the mesh, the less it contributes to the differences between simulation and reality and it can conclude that a fine mesh will always give a better result. It can be seen in Fig. 5 that the von Mises stress is almost similar between the following mesh sizes: 40, 50 and 60 mm. As it is observed there is no significant difference between the coarse mesh and the refined mesh up to the 6th sizes. One can also notice that there is hardly any difference between coarse mesh and the refined mesh for all the different sizes.

In Figs 6 and 7 the refined mesh of pitch equal to 40 mm is used to calculate under ABAQUS the transient response using the general type procedure and the Dynamic/Explicit option of the Step module. This allows a better spatial resolution.

3.4. Burst-tone excitation signal

Theoretically, for an elastic structure the obtained response has a frequency content that is driven by that of the excitation signal. According to [17], the obtained guided waves were shown to have a wavelet spectrum, which is compatible with that of the excitation signal. In the following, the excitation signal is taken to be sine wave modulated by a Hamming's window. It has for $0 \leq t \leq N/f$ the following form (8):

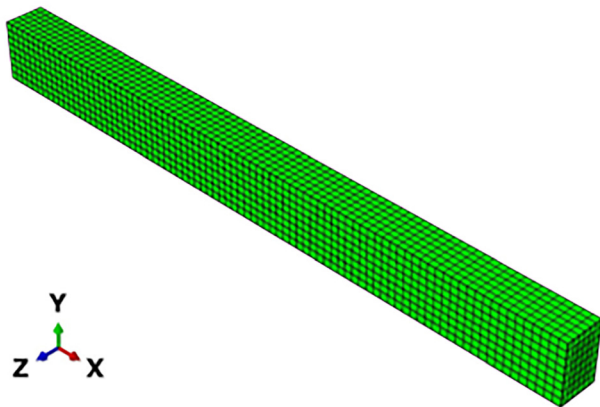


Fig. 6. The refined mesh used in finite element modeling, sizes 40 mm (Source: Author)

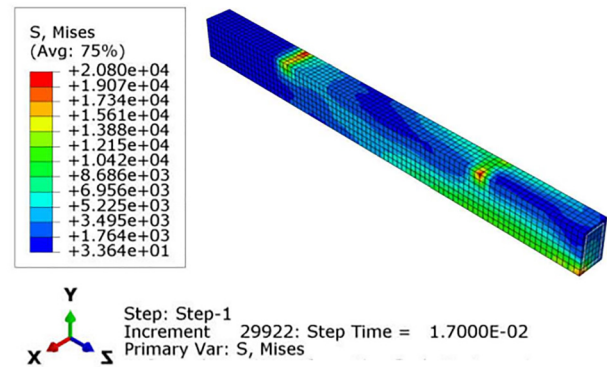


Fig. 7. The von Mises stresses with refined mesh 40 mm (Source: Author)

$$A(t) = \sin(2\pi ft + \theta) \left[0.54 - 0.46 \cos\left(\frac{2\pi}{N} ft\right) \right] \quad (8)$$

For $t \leq 0$ or $t \geq N/f$ the signal vanishes, so the excitation consists of a tone-burst like signal with N fixing the number of the cycles; f the central frequency and θ a phase parameter.

Lamb waves are formed from double waveforms (modes): ant-symmetric modes and symmetric modes due to its pattern and dispersion of the Lamb waves [18]. The software used to draw the dispersion curves for reinforcements with a diameter of 14 mm is disperse curve [19, 20]. The group speed is determined by the numerical method via the increment time between the input wave and the output for each stress signal as a function of the diameter of the rebar. Verification of the dispersion curves based on the group velocities that have been determined experimentally on the holy (undamaged) steel reinforcements, it can be seen that the only suitable form for our geometry and with less dispersion is 5 cycles with a center frequency of 50 kHz.

In this study, the excitation signal is centered on the work frequency $f = 50$ kHz and has 5 cycles. The maximum amplitude is fixed at 0.27. Figure 8 presents time variations and Fast Fourier Transformation FFT spectrum of this tone-burst signal.

Figure 9 shows the Fast Fourier Transformation (FFT), this excitation spectrum obtained by applying the fast Fourier transform, using the fft command from Matlab.

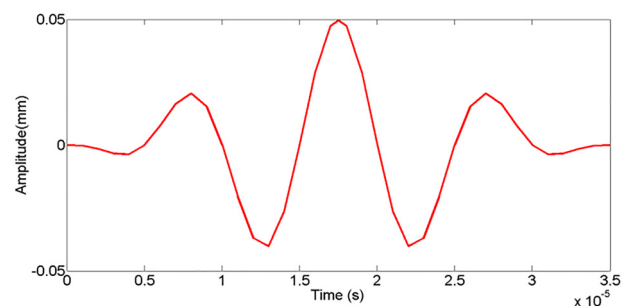


Fig. 8. Five-cycle tone-burst modulated at 50 kHz (Source: Author)

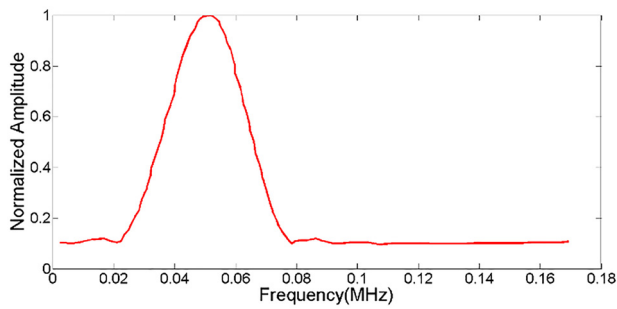


Fig. 9. FFT spectrum of the tone burst (Source: Author)

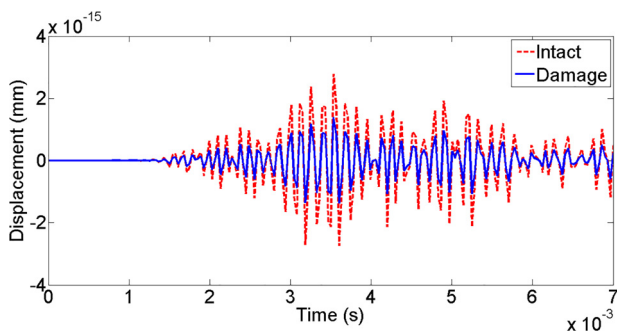


Fig. 10. Reflected waves from the intact and corrosion damaged beams (Source: Author)

The propagation of waves in two cases a healthy beam and the other damaged by corrosion is considered. When the wave enters the part of the defect, which has a degradation of the material due to corrosion, the displacement of the wave increases that is shown in Fig. 10. The ABAQUS/Explicit FE analysis was carried out to simulate the propagation in two cases a healthy beam and the other damaged by corrosion in tensile rebar. The result presented is a due response of a node sensor, the propagation of the incident Lamb wave in time as a function of the beam displacement, when the wave enters the part of the defect, which has a degradation of the material due to corrosion, the displacement of the wave increases. The result gives a clear view of the influence of damage in the structure.

4. CONCLUSIONS

The ABAQUS/Explicit FE analysis was carried out to simulate the propagation in two cases a healthy beam and the other damaged by corrosion in tensile rebar. The result presented is a due response of a node sensor, the propagation of the incident Lamb wave in time as a function of the beam displacement, when the wave enters the part of the defect, which has a degradation of the material due to corrosion, the displacement of the wave increases. The result gives a clear view of the influence of damage in the structure.

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