Damage detection in RC Beams Based on Wavelet Packet Analysis using PZT Sensors

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Abstract. The use of piezoelectric lead Zirconate Titanate (PZT) transducers is growing in the monitoring of large-scale engineering structures, such skyscrapers and bridges. PZT transducers are implanted in the surface to monitor structures using electro-mechanical impedance or electro-mechanical admittance with PZT and wave transmission with several PZTs. A broader region may be monitored by approach wave propagation with high voltage excitation. Because failure is unexpected and delicate, the condition of reinforced concrete (RC) members at lap splices provided at tension zone is closely observed. The goal of this work is to use PZT to identify damage to the RC beam at steel bar lap splices. PZT were attached on steel bars with varying lap spans to identify damage to reinforced concrete buildings at the steel bar lap zones. Four reinforced concrete beams were used for the tests. The tension bars were spliced in the constant moment zone at lap lengths ranging from 10 to 20 to 30 to 40 times the diameter of a bar (40). At the lap splices, two PZTs were placed separately on each steel rebar. One PZT patch served as an actuator, creating elastic waves that another PZT patch, acting as a sensor, converted into electric impulses and recorded. The signals received were analyzed using wavelet packets and the results were presented.

Keywords: Structural health monitoring, PZT Transducers, Lap Splices, Damage Index, wavelet Packet, piezoelectric sensors

1 Introduction

Researchers have been in strong agreement for the past 20 years that the catastrophic consequences of failure are to blame for the inadequate performance of RC structures at numerous critical positions, including zones of lapping of steel re-bars and connections of beam & column. The breakdown of buildings as a result of the

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tension rebar's inadequate lap length is extremely erratic and fragile. There is less possibility of bar slipping or beam splitting before the yielding of steel bars when there is enough contact area between the lap splice and concrete. Research on an appropriate structural health monitoring (SHM) approach at the steel rebar intension zone lap splices is required to identify the early warning signs of a reinforced concrete structure collapsing.[1-3]

A new and efficient method for identifying RC structural damage is SHM, which uses piezoelectric or piezo-ceramic transducers. Its primary characteristics are its small size, low weight, affordability, active sensing, quick reaction time, and ease of use. It is simply attached to the surface or put into the structure [4-6]. Piezoelectric Lead zirconate titanate (PZT) is special because it generates surface charge when mechanical stress is applied and deforms mechanically when an electric field is applied. Wave propagation techniques are used with PZT transducers, which measure electromechanical impedance (EMI) or electromechanical admittance (EMA) to evaluate the structural health [7-8]. Because failure at tension lap splices is unpredictable and fragile, the state of RC pieces is constantly monitored. When comparing PZT patches to LVDT and conventional microscopes for the early detection of concrete structure deterioration, it becomes evident that Structural Health Monitoring (SHM) with PZT patches is more dependable than earlier techniques. The EMI method may be used for routine structural checks and is more sensitive in spotting early degradation. [9-10]

SHM employing PZTs and the Wave Propagation Technique

The use of PZT transducers in the wave propagation approach for structural health monitoring has garnered more interest and study in recent times. The physical boundary conditions of the system play a major role in the solution of the guided wave's governing equation. [11-12] Stress waves are often propagated through steel re-bars, beams, using the wave propagation technique. The limits of the host structure guide the stress waves, which then spread throughout the structure and may be felt to identify areas that are damaged.[13-15]

2 Methodology

Wavelet Packet Analysis

The signal processing technique employed in this work to verify the gathered data was wavelet packet analysis. The initial use of wavelets was in the analysis of seismic data. The wavelet packet is being used to analyse the signal data instead of the Fourier Transform (FT) that was used initially. Fourier transform analysis splits the signal into waves with different frequencies, whereas wavelet analysis splits the signal into shifting and scaling wavelets generated at origin. The PZT sensor uses a wavelet method to identify the signals and break them down into smaller signals. The energy vector is created using the energy of the broken signal. The energy vectors of the damaged and healthy states are compared to calculate the damage-index, which is used to gauge the extent of damage in RC beams.

The current algorithmic process adheres to the recommendations of standard literature. One side of the specimen is equipped with Ns numbers of PZT sensors. Each PZT sensor's associated energy is defined as the energy vector's 1-norm as follows:

$$E_k=\sum_{i=1}^{2^N} e_{k,i},\ (k=1, N_s) \quad (1)$$

Damage Index

Different indices of damage have been utilized for structural health monitoring systems that take into account civil structures. As a handy damage index, the Root Mean Square Deviation (RMSD) examines the differences between the signatures of a healthy state and a damaged state. The best damage index for identifying and characterising defects in concrete buildings is the root mean square deviation (RMSD) between the signatures obtained from the PZT transducer. The root mean square deviation (RMSD) of the energy vectors in both the healthy and damaged states is the definition of the Damage Index (DIE) in this study.

The damage index formula is,

$$DI_E = \sqrt{\frac{\sum_{i=1}^{2^N}(e_{k,i}-e_i^h)^2}{\sum_{i=1}^{2^N}(e_i^h)^2}} \quad (2)$$

If e k i is the energy of the fragmented signal and ehi is the energy level corresponding to the healthy state, which served as a reference for damage detection. The transmission energy loss brought on by the damages is represented by the equation above. Conversely, a healthy state is indicated by a low damage index number. The damages increase with the index values.

3 Experimental Work

In order to cause failure in the tension zone, four concrete beams strengthened with supplied steel rebars spliced in the constant moment area were tested. Under bending, the 200 x 250 mm cross-section RC beams with a 2700 mm length were cast as a single reinforced rectangular piece. It was tested using a four-point bend arrangement and was simply supported at a distance of 2250 mm from centre to centre of supports. Two high-grade steel deformed bars measuring 16 mm in dia were used as tension reinforcement for the specimens, while two numbers of bars measuring 12 mm in diameter were used for compression reinforcement, and stirrups were used for shear reinforcement.

In order to induce failure in the tension zone, four concrete beams reinforced with premium steel bars spliced in the constant moment area were put through testing. The 2700 mm long, 200 x 250 mm cross-section RC beams were prepared as a single rectangular piece under bending. It was just supported at a distance of 2250 mm from the centre to the centre of supports and tested using a four-point bend configuration.

Two high quality steel deformed bars with a diameter of 16 mm were used as tension reinforcement, two amounts of bars with a diameter of 12 mm were utilised as compression reinforcement, and stirrups were used as shear reinforcement.

At one of the tension steel bars, PZT 1 and PZT 2 were positioned, and at another tension steel bar in the lap zone, PZT 3 and PZT 4 were positioned. PZT 2 and 4 served as detectors to detect and measure and note the signals, while PZT 1 and PZT 3 on steel rebar served as actuators to produce high-frequency waves. Epoxy glue was used to adequately bind them to the steel bars. A thin coating of epoxy glue was used to provide a waterproof covering on the installed PZT transducers in order to guard against PZT patches becoming damaged during the concrete casting process. As seen in Figure 1, strain gauges were positioned at the Start (S1), Middle (S2), and End (S3) of the lapped bar in the lap zone in order to examine the strain characteristics of the spliced steel re-bars.

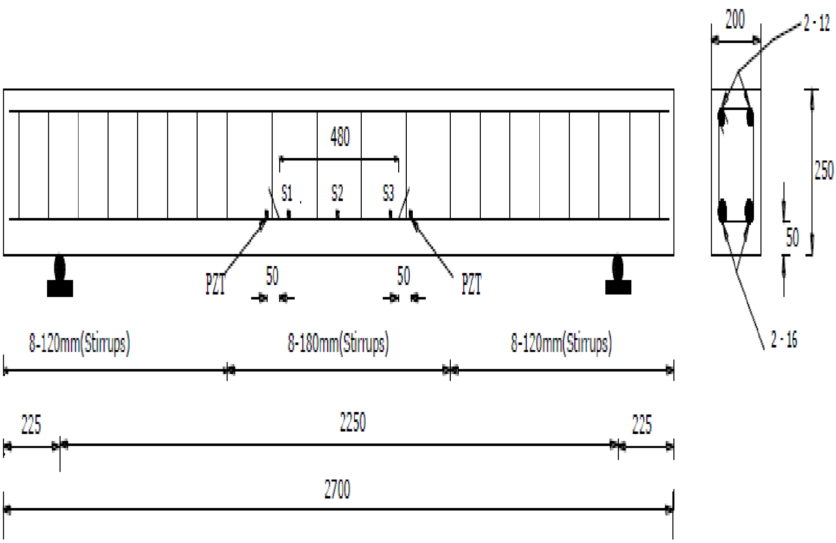

Fig.1. Cross section of the RC Beam

In the present study, loading with a cyclic scenario was adopted. The structure was released at zero kN after being loaded at 10 kN initially. For the 10ϕ lap splice beam, 68 kN for 20ϕ lap join beam, 96 kN for 30ϕ lap splice beam, and 128 kN for the 40ϕ lap spliced beam, the load was progressively raised and emptied to zero kN until the failure load was reached. The hydraulic jack applies the load centrally, distributing it evenly over the beam's two loading points. To assess the kind of failure, the crack's initiation and propagation were monitored and seen on the beam's surface after each loading.

4 Results and Discussions

A cyclic loading pattern was applied in this research. After being loaded to 10 kN, the structure was released to zero kN. The value were observed to gradually increased and released to zero kN, and this process continued until the lap splice beams for 10ϕ, 20ϕ, and 30ϕ laps were spliced at 42 kN, 68 kN, and 128 kN, respectively, failed. The hydraulic jack applies the load centrally, distributing it equally between the beam's two loading points. Following each loading, the crack's initiation and propagation were monitored and seen on the beam's surface to determine the kind of failure. Results were given in Tables 1 to 4.

Table 1. Results for Beam of 10ϕ lap splice

Sl. No.	Load in kN	Damage Index (DIE)	
		PZT 2	PZT 4
1	10	0	0
2	12	0	0.0231
3	14	0.02653	0.04346
4	18	0.19425	0.21234
5	20	0.22764	0.242766
6	22	0.25347	0.263428
7	24	0.97962	0.989362
8	30	0.98129	0.989362
9	40	0.99234	0.995745
10	42	0.99574	0.995745

Table 2. Results for Beam of 20ϕ lap splice

Sl. No.	Load in kN	Damage Index (DIE)	
		PZT 2	PZT 4
1	10	0	0
2	14	0	0
3	16	0.02345	0
4	20	0.07342	0.06015
5	24	0.15894	0.136749
6	30	0.25671	0.225564

7	34	0.32063	0.297345
8	36	0.97456	0.984962
9	40	0.98564	0.984962
10	50	0.98872	0.992481
11	60	0.99123	0.995489
12	68	0.99774	0.99762

Table 3. Results for Beam of 30ϕ lap splice

Sl. No.	Load in kN	Damage Index (DIE)	
		PZT 2	PZT 4
1	10	0	0
2	20	0	0
3	26	0	0
4	30	0.05643	0
5	40	0.15786	0.130435
6	44	0.220867	0.202789
7	50	0.29453	0.277174
8	56	0.36099	0.387544
9	60	0.45362	0.467391
10	66	0.64037	0.650935
11	68	0.85765	0.83459
12	70	0.90121	0.90459
13	72	0.95734	0.98913
14	80	0.96742	0.98913
15	90	0.98566	0.99456
16	96	0.99728	0.99712

Table 4. Results for Beam of 40ϕ lap splice

Sl. No.	Load in kN	Damage Index (DIE)	
		PZT 2	PZT 4
1	10	0	0
2	20	0	0
3	30	0	0
4	34	0	0
5	38	0	0.0432
6	40	0.04213	0.07419
7	50	0.16346	0.19677
8	60	0.28363	0.30161
9	70	0.45168	0.46451
10	76	0.58547	0.60645
11	80	0.86782	0.84290
12	82	0.92011	0.91249
13	84	0.97474	0.98709
14	90	0.97895	0.98709
15	100	0.98579	0.99032
16	110	0.99126	0.99354
17	120	0.99437	0.99677
18	128	0.99677	0.99677

In BS10, damage level 1 refers to the initial crack that appeared on the beam when the load value reached 22 kN. In a similar vein, the beam nearly collapsed at the ultimate load magnitude of 42 kN; this condition is known as damage level 2. Both damage levels 1 and 2 were used to measure the signatures. There are some differences between the two damaged and healthy levels that have been recorded from the bonded PZT 2 and PZT 4 on tensile steel bars of BS10 beam, particularly in the frequency band of 30 kHz to 90 kHz, according to the comparison of the response curves .

When the load value in BS20 reached 28 kN, the first fracture in the beam started, and this condition is known as damage level 1.When the load value hit 50 kN, the damage level 2 was referred to. Likewise, the beam nearly disintegrated at the ultimate load magnitude of 68 kN; this condition is referred to as damage level 3. Measurements of the signatures were made at damage levels 1, 2, and 3. Particularly in the frequency band of 30 kHz to 90 kHz, there are some discrepancies between the three damaged and healthy levels as determined by the bonded PZT 2 and PZT 4 on tensile steel bars of BS20 beam.

When the load value reached 42 kN in BS30, damage to the beam started, which is referred to as damage level 1. The damage levels 2 and 3 were obtained when the load values reached 70 kN and 80 kN. In a similar vein, the beam almost failed at damage level 4 with an ultimate load of 96 kN. We obtained the signatures at damage levels 1, 2, 3, and 4. The healthy and three damaged levels measured from the bonded PZT 2 and PZT 4 on steel bars of BS30 beam show some variances particularly in the frequency region of 30 kHz to 90 kHz.

The BS40 beam began to fracture when the stress reached 48 kN. This is known as level 1 damage. Referred to as damage levels 2 and 3, respectively, when the load values approach 80 kN and 100 kN. Similarly, the beam, designated as damage level 4, almost disintegrated with an ultimate load of 128 kN. Signs were noted for damage categories 1, 2, 3, and 4. The healthy and three damaged levels recorded from bonded PZT 2 and PZT 4 on steel bars of BS40 beam varied somewhat, as the figures below demonstrate, especially in the frequency region of 30 kHz to 90 kHz.

Figures 1 to 3 illustrate the ultimate failure mechanisms and beam crack patterns at the lap splices of tensile steel bars on both sides of the beams.

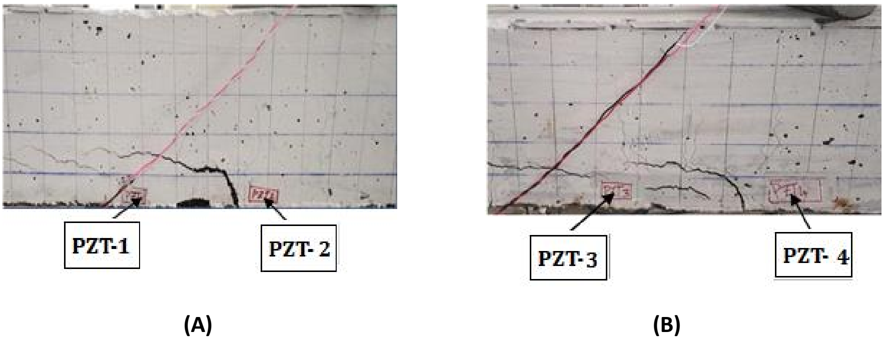

Fig.2. (A), (B) crack patterns on both sides of BS10 at lapped zone

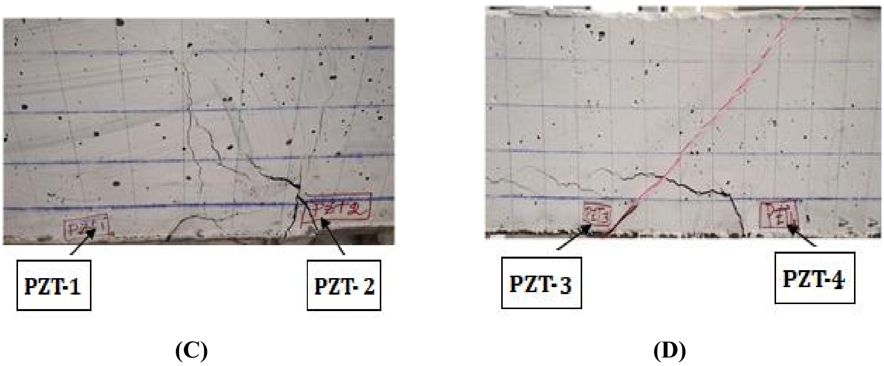

Fig.3. (C), (D) crack patterns on both sides of BS20 at lapped zone

The Damage Index (DIω) histogram of the analysed damage levels of PZT sensors fixed splices of all beams; four PZTs (PZT 1, PZT 2, PZT 3, and PZT 4) were installed on tensile steel bars. Utilizing PZT sensors (PZT 2 and PZT 4) attached to all tensile steel bars on both sides of RC beams, the signal measurements of each damage level were carried out. It is evident from results that when damage levels rise, so do the Damage Indices (DIω), which are derived from signal measurements of all installed PZTs.

Damage Index (DIω) histogram were examined to assess damage levels of PZT sensors attached to the tensile steel bars of beams BS10, BS20, BS30, and BS40. Four PZTs were mounted on tensile steel bars at the lap splices of all beams. Each damage level's signal was measured using PZT sensors (PZT 2 and PZT 4) that were fastened to every tensile steel bar on both sides of RC beam. Damage Indices (DIω), are based on signal measurements from all installed PZTs, increase in tandem with damage levels.

COMPARISION OF DIE VERSUS Diω:

Using wavelet packets and signal data derived from frequency response curves, the RMSD values between the healthy and damage states of the energy vectors of decomposed signal data were used in this work to evaluate the damages appeared on RC structures at lap splices of steel bars. "Damage indices" were used to describe these RMSD values. The Damage Index (DIω), which is based on the frequency response curve, solely shows the failure progression. The experimental results show that the Damage Index (DIE) created by wavelet packet analysis agrees with measurements made by conventional sensors such as LVDTs and microscopes.

This indicates that the recommended DIE values, which are derived from the wavelet packet analysis approach, are effective in classifying the brittle and yielding failure behaviour in the lap splices of steel bars and in identifying the existence of cracks inside concrete buildings. As a result, the proposed DIE outperforms the conventional DIω in predicting the collapse of reinforced concrete buildings at steel bar lap splices.

5 Conclusions

The thorough studies led to the following conclusions out of the research:

1. The suggested gearbox energy-based damage index is a better gauge of the existence and extent of internal fractures.
2. The PZT demonstrated extraordinary sensitivity in identifying splitting and ductile failure of flexure at the zones of lap slices of the steel re-bars.
3. The suggested method successfully detects failure and finds cracks in the material. In comparison to traditional methods, it also makes full structural damage identification faster. Furthermore, it acts as a warning before brittle breakdown causes the structural collapse.
4. Flexural cracks and splitting crack initiation may both be accurately detected by a wavelet packet-based structural damage index, which can also provide consistent values to track the progression of crack severity till structural collapse.

This indicates that the recommended DIE values, which are derived from the wavelet packet analysis approach, are effective in classifying the brittle and yielding failure behaviour in the lap splices of steel bars and in identifying the existence of cracks inside concrete buildings. As a result, the proposed DIE outperforms the conventional DIω in predicting the collapse of reinforced concrete buildings at steel bar lap splices.

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