Application of genetic algorithm in damage detection of reinforced concrete beams using piezo ceramic transducers

R Mohanasundari and C Vijayaprabha
Alagappachettiar Government College of Engineering & Technology, Karaikudi-3, India

Email: ravimohanasundari@gmail.com and vijayaprabha.struct@gmail.com

Abstract. Health monitoring of reinforced concrete bridges and other large-scale civil infrastructures has received considerable attention in recent years. However, traditional inspection methods (x-ray, C-scan, etc) are expensive and sometimes ineffective for large-scale structures. Piezo-ceramic transducers have emerged as new tools for the health monitoring of large-scale structures due to their advantages of active sensing, low cost, quick response, availability in different shapes, and simplicity for implementation. This study presents an experimental effort for the detection of damages in the reinforcement bars at lap zone of the reinforced concrete beams using Piezo-ceramic Transducers (PZTs) with the help of Genetic Algorithm (GA). An Electromechanical admittance (EMA) approach is used to evaluate the damages in the RC beams for standard lap length provided in IS 456 code and optimized lap length of bars. Tests are performed in i) steel reinforced bars with standard lap length embedded in a reinforcing concrete beam of 1.3m span subjected to flexural load for detecting the response and damages ii) steel reinforcing bar with optimized lap length given to a reinforced concrete beam of span 1.3m subjected to flexural load for detecting the response of healthy state beam. Test measurements of healthy and damaged steel bars in the lap zone of the reinforced concrete beam have been conducted using the developed monitoring system and piezo ceramic transducers.

Keywords: Piezo-ceramic transducers, Lap length, Compressive strength, Flexural load, Damage detection, Genetic Algorithm

1. Introduction
As new materials and technologies are discovered, buildings get taller, bridges get longer spans and the designs of structures become more ambitious, but more complex. In view of these developments, there is an increased requirement for providing both the cost savings with regard to maintenance and a safer environment by preventing structural failures. The design, fabrication, and construction of smart structures are one of the ultimate challenges to engineering researchers today. Because, they form the essence of system intelligence, one of the cores of smart structures technology centers on innovative sensors and sensor systems [1]. Structural health monitoring (SHM) represents one of the primary applications for new sensor technologies. Indeed, much attention has been focused in recent years on the declining state of the aging infrastructure, as well as to the limitation of their responses during extreme events (such as wind and earthquakes). Structural Health Monitoring (SHM) is a process aimed at providing accurate and in-time information concerning structural condition and
performance on a proactive basis. It consists of (i) permanent continuous, (ii) periodic or (iii) periodically continuous recording of representative parameters, over short or long terms. The information obtained from monitoring is generally used to plan and design maintenance, increase the safety, verify hypotheses, reduce uncertainty and to widen the knowledge concerning the structure being monitored[4].

1.1 Admittance based structural health monitoring technique

SHM based on the electro-mechanical admittance (E/M) is a simple and straightforward approach[5]. The basic concept of the method is to verify changes in the mechanical admittance of the monitored structure and compare the scenarios with and without damage. The measurement of the mechanical admittance is performed indirectly through the electrical admittance measurement with the aid of piezoelectric transducers coupled to the monitored structure or incorporated to it. The measurements are performed both for the pristine condition (baseline) and during the lifetime of the structure. Considering the coupling properties between the PCT patch and the structure, the presence of damage can be verified by observing the change in the signal of the electrical admittance. This change can be quantified with the aid of properly defined damage metrics. One of the first published reports on this subject for civil structures showed that the electromechanical admittance method was successful for crack detection in the context of loading and unloading of a prototype formed by a part of a bridge[4]. This structure was made with reinforced concrete. Other studies have also obtained promising results such as, for example, in detecting damage in concrete plates where the damage was produced from a cutting blade. In another study, the influence of the concrete cure on the admittance signals was considered. For this aim, a piezoelectric transducer was introduced in the concrete plate during its manufacturing. It was found that the admittance signals change as the samples were subjected to compression; however, the authors did not conduct more detailed studies in the presence of incipient damage during the tests. A study about the influence on the admittance signals of the detachment of the piezoelectric transducers was also performed. In this case, the sensors were bonded to the steel fibers used to reinforce concrete structures [11]. In another study, the technique was used to detect carbonation in this type of structures. The influence of temperature and loading on the admittance signals of a piezoelectric sensor coated with a protection structure with cement and epoxy was also investigated. In a recent work, a wireless monitoring system based on admittance signals was developed. The admittance signal module was used for damage prognosis in a reinforced concrete structure (RC-Beam) [8].

In this regard, a network of sensors was incorporated both in the inner and outer parts of the structure however, when using the admittance module, it should be considered that the admittance signals incorporate the imaginary part of the admittance signal since it depends on temperature variation (figure 1). Based on this last contribution, the objective of the present work is to develop an experimental test using the real part of the admittance signal to detect damage in a prismatic sample of concrete reinforced with steel fibers. This specimen was subjected to toughness testing, aiming at producing an incipient damage. In addition, the influence of temperature on the admittance signal was evaluated and compensated.
2. Experimental procedure

2.1 Materials used
Ordinary Portland Cement of 43 grade confirming to IS 8112:2013 was used. The specific gravity of cement is equal to 3.14. The specific gravity fine aggregate and coarse aggregate were found to be 2.61 and 2.68 respectively. Figure 2 shows the gradation curve of fine aggregate and gradation limits of zone I and zone II as per IS 383-1970. The particle size distribution represents that the sand comes under zone II which is suitable for concrete works. Complast SP-430 is used as a high range Naphthalene based super plasticizer conforming to IS 9103-1999 admixed to avoid segregation, to improve the flow ability and also to ensure thorough dispersion of particles in the concrete mix.

2.2 Mix design
The mix shall be designed to produce the M25 grade of concrete having the required workability and characteristic strength not less than appropriate values given in the IS 456:2000.
2.3 Design stipulations
Type of cement: OPC 43 grade
Max. size of aggregate: 20 mm
Exposure condition: Moderate
Workability: 75 mm (Slump)
Maximum water cement ratio: 0.5
Minimum cement content: 300 kg/m³
Type of Aggregate: Crushed Angular aggregate
Super plasticizer will be used
Specific gravity of coarse aggregate: 2.8
Specific gravity of fine aggregate: 2.67
Target mean strength = 31.6 MPa
As per the Indian codal provision IS 456: 2000 based on exposure condition, w/c ratio = 0.55
Mix proportions: 1: 2.325: 3.255.

Table 1 gives the quantities required per cubic meter of concrete.

| Material                        | Quantity  |
|---------------------------------|-----------|
| Cement (kg/m³)                  | 350       |
| Fine Aggregate (kg/m³)          | 814.015   |
| Coarse Aggregate (kg/m³)        | 1140.6    |

2.4 Compressive strength of Concrete

The slump test was performed according to IS 1199-1959. For 0.5 water cement ratio the height of slump is 70 mm which is coming under medium workability. Hence the designed mix achieved the required slump value. The average compressive strength at 7 and 28 days are 24.4 MPa and 33.18 MPa respectively. The average compressive strength at 28 days (33.18 MPa) is more than the target mean strength of 31.6 MPa. The average compressive strength at 28 days is 5% more than the target strength.

3. Optimization of lap length

3.1 Lap length
As the name suggest, lap length is provided for overlapping two rebars in order to safely transfer the load from one bar to another bar.

We know that rebar come in a certain length. If the rebar needs to be extended beyond that limit then sufficient lap length to be provided to safely transfer the load.

Lapping is usually done where minimum bending stress is encountered. In general, lap length is 50d which means 50 times the bar diameter, if both bars are of same diameter.

3.2 Lap length in tension

The lap length including anchorage value of hooks shall be
• For flexural tension - \( L_d \) or 30d whichever is greater
• For direct tension – 2\( L_d \) or 30d whichever is greater
• The straight length of lapping shall not be less than 15d or 20cm.

3.3 Lap length in compression

The lap length in compression shall be equivalent to the development length in compression computed but not less than 24d.

3.4 Lap length in beams

• Lapping (24d) in top bars avoided L/3 distance from both end. For top bar lapping should be at mid span.
• Lapping 45d in bottom bars lap should be provided at column junction or L/4 distance from column base but should not be in mid span of beam.
• Stirrups should be closely spaced near the columns and lose/normal at mid span.
• Lapping of bars should be alternately provided.

3.5 Limitations in providing lap length

• Lapping is not provided above 36mm diameter bars does not transfer the stresses from one bar to another bar and also the alignment of the column bars is also affected by provided lap on these bars.
• The lapping of the steel bars also not provided in high shear force zones and it should be provided at zone where shear force will be minimum.
• Lapping should be avoided in tensile zones of members under consideration, so in a continuous beam because of negative moment tension is at the top, near supports and tension is in bottom, at mid span, for columns, if you observe the bending moment diagram, generally the point of contra flexure is around mid height column, so lapping is to be done mid height of the column but always remember you need to see the bending moment diagram to decide lapping location.
• Lapping should be avoided in tensile zone of construction members. For column bending moment at mid point is zero so try to lap at mid point.

4. MATLAB Coding for optimization  [lap length and diameter as two unknown]

4.1. Mat lab

It is a high level language for numerical computation, visualization and application development. It also provides an interactive environment for iterative exploration, design and problem solving.

4.2. Fitness function

A fitness function is a particular type of objective function that is used to summarize, as a single figure of merit, how close a given design solution is to achieving that set aims. Fitness function is used in genetic programming and genetic algorithms to guide simulations towards optimal design solutions.

\[
\tau_{co} = \left[ 0.46 + 0.23 \frac{b_h}{d_b} + 14.85 / \left( \frac{l}{d_b} \right) \right] 0.313 \sqrt{\sigma_B} \tag{1}
\]

Where,
τ_{Co} - Calculated Bond splitting strength
Mu - Maximum bending moment
J – Effective depth
b_s - clearance

\[ b_{si} = b - \frac{\Sigma d_b}{\Sigma d_b'^{\prime}} \]

Where,
Σd_b - Sum of dia of bars in lap
Σd_b'^{\prime} - Sum of dia of bar outside lap
b - Beam width

4.3. Fitness function coding

Function \( b = \) lap splice length \( (X) \)
\[ b = (0.456 + 0.656 + \frac{14.85}{x(1)})* (0.313 * \sqrt{25}); \] (2)

4.4. Constraints

In mathematical optimization, constrained optimization is the process of optimizing an objective function with respect to some variables in the presence of constraints on those variables.

4.5. Condition used as constraints

Min. lap length condition as per IS456: 15d;
Min. diameter of the reinforcement: 6mm;
Max. Diameter of the reinforcement: 36;
Max. Lap length condition as per IS 456:50d;

\[ \tau_{uexp} = \frac{M_u}{j*\psi*l*d} \] (3)

**Bond stress** = \[ \frac{M_u}{j*l*d*P} \] (4)

P= perimeter of the reinforcement bar \((\pi*d)\)
j = lever arm = \( \frac{7}{8} \)*d; where, d=depth of beam;
\( L_s \)>30d
\( L_s \)>15d
\( >200\)mm
\( L_s \)>50d

4.6. Constraint coding

The following MATLAB codings are used for developing constraints or boundary conditions. \( C_{eq} \) is the equivalent constraint calculated by considering all limitations of lapping length. Substituting all constraints equation \((4)\) can be written as equation \((5)\).

Function \([c, ceq] =\) lapsplicecon1 \((x)\)
\[ C = x(1) - 15 * x(2); \]
\[ x(2) - 6; \]
\[ 36 - x(2); \]
\[ 50 * x(2) - x(1); \]
\[ (43125000/((7/8) * 250 * 3.14 * x(1))) == 0.84; \]
\[ Ceq = [ ] \] (5)

Ceq = [ ]
5. Experimental setup of flexure test

The test program of this study includes the application of the adopted wave propagation technique procedure to large scale RC beams under flexural loading. Reinforcement details and cross sectional details are shown in Figure 3. This way, the effectiveness of the proposed method evaluates the damages caused on the tensional reinforcing bars of RC beams during a typical flexural test and at different levels of loading is investigated [9]. Thus three PZTs are used per RC beam: PZTs no 1, 2 and 3 is casted on the beam. They are epoxy bonded on the surface of steel bar after flattening of the bar. A water proof layer of the epoxy adhesive has also been applied meticulously on the top of the bonded PZT transducers in order to protect the patches during concrete casting and to avoid noise the PZT located at a distance of 100mm (Divsholi et al., 2014). A typical two – point bending scheme and setup is adopted for the flexural test of the RC beams (Figure 4), the imposed loading was applied at two points 400 mm apart from the end of the span.

![Figure 3. Reinforcement details](image1)

![Figure 4. Experimental setup](image2)

5.1. Flexure test on RC beam

The imposed load was consistently increased at that time the signals are recorded continuously. The mounted PZTs were recorded at different levels of the applied flexural loading using the experimental set-up of the adopted wave propagation procedure.

A cyclic loading scenario was adopted in this study. The RC beam 1 was gradually loaded to 15, 25, 35, 45, 55, 65, 75 kN and so on up to failure (245 kN). The RC beam 2 was gradually loaded to 15,
30, 45, 60, 75, so on up to failure (300 kN). These values referred to the central load generated by a jack in universal testing machine. Then it was equally distributed to the two loading points and applied on the beam. The propagations of cracks after each loading were marked on the surface of the beam. A typical two-point bending scheme and setup is adopted for the flexural test of the RC beams. The beam was simply edge-supported on roller supports apart from each other using a rigid laboratory frame. Measurements for load and deflection were read and recorded continuously during the tests.

After undertaking the tests, the UTM was used to subject the reinforced concrete beam with different loading cycles of increasing amplitudes and varying time duration. The loading cycles were of sinusoidal wave form with a frequency embedded in the RC beam. The displacement amplitudes during cyclic load application were 6.1 mm, 7.0 mm, 7.5 mm, 8.5 mm and 16 mm. The smaller amplitudes used in first two applications were specifically chosen to enable. During loading process in the beam smart aggregate as act sensor. The recording of signals before crack like damages developed in the beam. In the process, the recorded signals were caused by background events like environmental noise, rubbing between the beam and supports, friction between the concrete and reinforcement, etc. A general view of the test setup, showing the close-up view of the crack and locations of beam, gages and sensors can be seen.

![Figure 5. Structural response of standard lap length RC beam (proper lapping)](image)

![Figure 6. Structural response of Optimized lap length RC beam (in sufficient lapping)](image)

![Figure 7. Comparison between healthy and damaged state of beam 1 having standard lap length](image)
Figure 8. Comparison between healthy and damaged state of beam2 having optimized lap length

Figure 9. Comparison between a state of optimized lap length and standard lap length of at a frequency of 60 KHz.

The experimentally measured time histories of the intensity of the current (or simply current) passing through PZT1 for the RCC beam with are compared. The comparisons of these diagrams point out that there are some differences easily detected between the response of the Beam with standard lap length and beam with optimized lap length. These discrepancies are mainly observed at the peak current points. Tested RC beams exhibited typical flexural response, as it has been designed and expected. The structural response of RC beams with lapping and with insufficient lap length is shown in Figure 5 & Figure 6. First flexural cracks formed in the mid-span (pure bending region) and perpendicular to the longitudinal axis of the beam 1 due to insufficient lap length. The increase of the applied load caused flexural cracks area to spread and inevitability tensional longitudinal bars to yield. In beam 2 the diagonal and vertical cracks (shear failure) are formed due to sufficient lap length. Signature of mounted PZTs on the steel bars of the RC beams were measured at the healthy state and the damage state of the beam 1 and beam 2 shown in figure 5 and figure 6 respectively. The frequency excitation of PZT is equal to 10 to 70 kHz. Concerning the test results of Beam-1 and Beam-2, Figures 7, 8 and 9 display the measured time histories of the current passing through PZT No. 1 at a voltage 7 volt, under different loading condition (15,25,35,45,55 up to failure). This is also attributed to the physical meaning of conductance that is the resistance of the material to electric current in the case of alternant load [11,12]. It should be noted that the presented SHM procedure has two obvious limitations concerning its application in existing structures: (a) The test setup of the adopted EMA technique is
not portable and (b) bonded piezoelectric transducers on the RC Beam are not applicable in existing RC structures, since they should be installed prior concrete casting. However, it would be very useful to practice if this methodology could be properly modified and extended in order to be applied in real and existing structures. A miniaturized, wireless, portable, lightweight, real time admittance monitoring system has already been developed to monitor early-age concrete compressive strength gain and to evaluate the structural integrity assessment of RC members using a smart piezoelectric sensor network.

Table 2. Load, bending moment and deflection values of Beam 1

| Load(kN) | Bending moment(kNm) | Deflection(mm) |
|----------|---------------------|---------------|
| 20       | 1.700               | 0.3           |
| 45       | 3.825               | 0.7           |
| 65       | 5.525               | 1.1           |
| 105      | 8.925               | 1.9           |
| 145      | 12.325              | 2.7           |
| 160      | 13.600              | 2.9           |
| 180      | 15.300              | 3.4           |
| 200      | 17.000              | 3.9           |
| 240      | 20.400              | 6.3           |

Table 3. Load, bending moment and deflection values of Beam 2

| Load(kN) | Bending moment(kNm) | Deflection(mm) |
|----------|---------------------|---------------|
| 25       | 1.260               | 0.2           |
| 65       | 5.330               | 1.4           |
| 100      | 8.500               | 2.3           |
| 125      | 10.625              | 2.9           |
| 165      | 14.050              | 3.9           |
| 185      | 15.725              | 4.4           |
| 200      | 17.000              | 4.9           |
| 245      | 20.825              | 6.1           |
| 310      | 26.350              | 11.2          |

Table 2 and Table 3 give the load, moment and deflection values of beam1 and beam 2. Structural response of the reinforced concrete beam 1 and beam 2 are represented in Figure 10 & Figure 11. Beam 1 loaded up to 240kN and Beam 2 loaded up to 310kN Load deflection curve taking linear profile up to 180 kN when proper lapping was used while beam 2 shows linear profile up to 160kN when the lapping was insufficient. Regression analysis gives polynomial equations (6) and (7) with 0.996 and 0.997 regression coefficient respectively for beam1 (proper lapping) and beam2 (insufficient lapping).

\[
y = -0.180x^2 + 4.416x - 0.245 \quad \quad R^2 = 0.996
\]  
\[
y = -0.418x^2 + 5.945x - 0.303 \quad \quad R^2 = 0.997
\]
where, \( y \) - Moment in kNm; \( x \) – Deflection in mm

![Graph showing Moment vs Deflection for Beam 1](image1)

**Figure 10.** Moment vs Deflection of Beam 1

![Graph showing Moment vs Deflection for Beam 2](image2)

**Figure 11.** Moment vs Deflection of Beam 2

\[
y = -0.1808x^2 + 4.416x - 0.2451
\]

\( R^2 = 0.9966 \)

\[
y = -0.418x^2 + 5.9452x - 0.303
\]

\( R^2 = 0.9971 \)
6. Damage index

6.1. Definition

It is defined as the ratio between the initial and the reduced resistance capacity of a structure, evaluated by using an evolution equation for the yield strength in which the structural damageability is included. An effort for the quantification of the damage detection using the root mean square deviation (RMSD) between the healthy condition and damage state of the sensor PZT is attempted. The numerical value of the RSMD yields a level for the difference between the healthy and the damaged admittance computation indicating this way the presence of damage in the structure. Table 4 indicates the damage indices and corresponding state of structure.

\[
RMSD = \sqrt{\frac{\sum |Y(j\omega)| - |Y(j\omega)|^2}{\sum |Y(j\omega)|^2}}
\]

Where,

\[ |Y(j\omega)|_d \] is the absolute value of the admittance of the PZT at the examined damage state,

\[ |Y(j\omega)|_o \] is the baseline value of the admittance(healthy state)

6.2. Damage index coding using MATLAB

Clear all;
Clc;
Disp (‘FINDING THE DAMAGE INDEX’)
Yd = [4 -5 6];
Yo = [1 2 -3];
Count=3;
Numerator =0;
Denominator=0;
For i=1:count
Diff = abs (Yd (i))-abs (Yo (i));
Numerator = numerator + diff.^2;
Denominator = denominator + (abs (Yo (i)).^2);
End
RMSD = sqrt (numerator/denominator);
RMSD

| Table 4. Interpretation of damage index |
|----------------------------------------|
| Degree of damage | Damage index | State of structures |
|-------------------|--------------|---------------------|
| Minor             | 0.0 – 0.2    | Serviceable         |
| Moderate          | 0.2 – 0.5    | Repairable          |
| Severe            | 0.5 – 1.0    | Irreparable         |
| Collapse          | >1.0         | Loss of storey or buildings |
7. Conclusion
The utilization of the EMA methodology for the detection and evaluation of the damage in the steel reinforcing bars of RC members using PZTs has been presented. Experimental measurements of healthy, damaged state of Beam with standard lap length and Beam with optimized lap length of large scale flexural RC beams have been carried out using an integrated experimental monitoring system and the signatures of mounted PZTs transducers. The signatures of mounted PZTs acquired from test measurements exhibited obvious discrepancies between the response of the healthy and the examined damage levels. Differences clearly indicated the presence of damage. According to flexural tests on RC beams under the different damage levels examined, flexural damages such as concrete cracking and steel bar elongation and their locations could be identified by using PZTs. The sensitivity of the PZTs in damage detection, their influence locus and the determination of damage location is investigated using signature comparisons, and RC beams cracking patterns observations. It is obvious that the level of the applied strain influences the material properties associated with the wave propagation properties; therefore the caused change of wave propagation properties due to strain caused by damage can be considered as the key of the efficiency of the applied technique.

References

[1] Annamdas, V.G.M., Soh.C.K. 2010 Application of electromechanical impedance technique for engineering structures: review and future issues. Journal of Intelligent Material Systems and Structures, 21(1):41-59, DOI: 10.1177/1045389X09352816

[2] Bhalla. S., Soh, C.K 2004 Electromechanical impedance modeling for adhesively bonded piezo-transducers. Journal of Intelligent Materials Systems and Structures. V 15 (12), 955-972,doi.org/10.1177/1045389X04046309

[3] Bhalla. S., Soh, C.K 2004 Structural health monitoring by piezo-impedance transducers. Modelling, Journal of Aerospace Engineering 17(4). DOI: 10.1061/(ASCE)0893-1321(2004)17:4(154)

[4] Bhalla. S., Soh, C.K 2004 High frequency piezoelectric signatures for diagnosis of seismic/blast induced structural damages. NDT &E International, 37, 23-33

[5] Bhalla., A.P.R. Vittal, M. Veljkovic 2012 Piezo-impedance transducers for residual fatigue life assessment of bolted steel joints. Journal of Structural Health Monitoring, 11(6):733–750, DOI: 10.1177/147592171245870.

[6] Chalioris.C.E., Providakis,C.P., Favvata,M.J., Papadopoulos,N.A., Angeli,G.M. and Karayannis,C.G. 2015 Experimental application of a wireless earthquake damage monitoring system (WiAMS) using PZT transducers in reinforced concrete beams. WIT Trans. Built. Environ. at Opatija, Croatia, 152, 233-243. DOI: 10.2495/ERES150191

[7] Chalioris, C.E., Papadopoulos,N.A., Angeli,G.M., Karayannis,C.G., Liolios,A.A. and Providakis,C.P. 2015 Damage evaluation in shear-critical reinforced concrete beam using piezoelectric transducers as smart aggregates. OpenEngineering,1,373-384, DOI: https://doi.org/10.1515/eng-2015-0046

[8] Divsholi,.B.S., Yang,Y., Bing,L. 2009 Monitoring beam-column joint in concrete structures using piezo-impedance sensors. Advanced Material Research, 79, 59-62, https://doi.org/10.4028/www.scientific.net/AMR.79-82.59.

[9] Divsholi,.B.S, Y. Yang 2012 Health monitoring of steel structures using sub frequency electromechanical impedance technique. Journal of Nondestructive Evaluation, 31, 197–207.

[10] Divsholi,.B.S, Y. Yang 2014 Combined embedded and surface-bonded piezoelectric transducers for monitoring of concrete structures. NDT &E International, 65, 28-34, https://doi.org/10.1016/j.ndteint.2014.03.009.

[11] Chalioris.C.E 2015 C.P. Providakis, M.J. Favvata, N.A. Papadopoulos, G.M. Angeli and C.G. Karayannis,2014 Detection of Concrete Reinforcement Damage Using Piezoelectric
Materials – Analytical and Experimental Study. World Academy of Science, Engineering and Technology. International Journal of Civil, Architectural, Structural and Construction Engineering, 8(2), 197-205.

[12] Chris G. Karayannis, Constantin E. Chalioris, Georgia M. Angeli, Nikos A. Papadopoulos, Maria J. Favvata, Costas P. and Providakis 2016 Experimental Damage Evaluation Of reinforced concrete steel bars using piezoelectric sensors. Construction and Building Materials, 105, 227-244, doi.org/10.1016/j.conbuildmat.2015.12.019.