Development of Concrete Damage Classification in Beam-Column Joint based on Ultrasonic Pulse Velocity

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Abstract. The concreted conditions assessment of the systems is an essential aspect of security assessment programs. In situ measurements of Ultrasonic Pulse Velocity (UPV) may be indicative of the level of damage in the original concrete. UPV influenced by the specific characteristics of the mixture. In situ UPV measurements can be indicative of the level of damage in the original concrete. The research purpose is the damage classification, UPV test interpretation (strength, density, elasticity modulus, Concrete Quality Designation (CQD)), and determines the level of structural damage visually so that more accurate inspection results. The research result showed that the plastic hinge was more damaged than other parts of the beam-column joints. The UPV test obtained density 0.84-1.03 g/cm³, CQD 10%-20%, static elastic modulus 7.68-8.39 Gpa according to [3],[4] including very poor and visually is included in category IV spalling off of covering concrete (crack width > 2mm). The use of UPV as supporting assessment for classification, repair, and maintenance of structures. If density, CQD, and elastic modulus of defining very poor classification, the structure that needs immediate repair. The use of UPV is faster, without damaging parts of the structure, and also induces damage to the core specimens as a result of the coring process, making it faster and more economical.

Keywords: concrete_damage, UPV, NDT, structure_assessment

1. Introduction

Many types of damage occur in concrete, including the expansion of thermal, alkali-silica reaction (ASR), plastic shrinkage, settlement, and electrochemical corrosion. The methods of testing are needed to find damage in concrete structures due to determine the internal integrity of these structures. A nondestructive test (NDT) methods for damage detection are available for assessing concrete strength in-situ. UPV methods were used to estimate the in-situ strength of concrete, density, and modulus of elasticity. The velocity of the wave propagation in the UPV method to identify the material quality and obtaining relatively conclusive results. The research method for improving test results was recorded by the ACI 228.1R-03[1] and ACI 318-14[2]. Recent studies have also indicated that UPV tests provide accurate results for estimating compressive strength and are influenced by different concrete properties[3],[4],[5]. The study uses the UPV approach, which is mostly accurate, efficient and scalable, which allow for an in-depth examination of material homogeneity. It is possible to assess concrete uniformity, to regulate its consistency, to track corrosion, to verify the existence of internal crack and voids, to allow comparisons with reference specimens, and to measure the capacity for compressive strength.

2. Nondestructive test (UPV) methods

The UPV approach has been known to provide a reliable means of measuring properties for some time and provide a unique potential for simple, precise, fast, safe, low cost and non-invasive quality control of buildings and other concrete destroyed by earthquake, fatigue or other catastrophic scenarios [6]. The UPV relies on the stiffness of the substances and its elastic properties. UPV is often used to calculate
the overall strength of the material and to determine its elastic properties [7]. One of the uses of UPV is the information of the Stiffness (Elasticity Modulus) [8],[9],[10],[11].

3. Damage classification of structural members

Classification of damage undertaken for the identification and measurement of damage to columns and beams. The load capacity of the vertical load and the lateral resistance of the column adjacent to the affected beam is reduced. Harm evaluation shall be conducted until the harm is observed in the projector. The definition of the injury type and the summary of the injury can be found in Table 1.

Table 1. Damage Class Definition of R.C. Columns and Beams [13]

| Damage Class | Description of Damage                                                                 |
|--------------|---------------------------------------------------------------------------------------|
| I            | - Visible narrow cracks on a concrete surface (Crack width is less than 0.2 mm)       |
| II           | - Visible clear cracks on a concrete surface (Crack width is about 0.2 -1.0 mm)       |
| III          | - The local crush of concrete cover                                                  |
|              | - Remarkable wide cracks (Crack width is about 1.0 - 2.0 mm)                         |
| IV           | - The remarkable crush of concrete with exposed reinforcing bars                     |
|              | - Spalling off of concrete cover (Crack width is more than 2.0 mm)                    |
| V            | - Buckling of reinforcing bars                                                      |
|              | - Cracks in core concrete                                                            |
|              | - Visible vertical and lateral deformation in columns and/or walls                   |
|              | - Visible settlement and/or leaning of the building                                   |

4. Materials and Experimental Program

The fourth specimen of reinforced concrete beam-column joints that weakness after hitting the ultimate load was examined for this analysis to assess the relative conditions of concrete based on measured pulse path length in the beam-column joints can be seen in Table 2.

Table 2. Description of beam-column connection specimens [12]

| Description       | Beam | Column |
|-------------------|------|--------|
| Dimensions (mm)   | 150 x 200 x 1000 | 200 x 200 x 750 |
| f’c (MPa)         | 21   | 21     |
| Longitudinal reinforcement | 4 Ø 13 | 4 Ø 13 |
| Fy (MPa)          | 580  | 580    |
| Stirrup           | Ø 8 – 100 | Ø 10 – 100 |
|                   | Ø 8 – 50  | Ø 10 – 50  |
| Fy (MPa)          | 440  | 440    |

The beam-column connection specimen is divided into three zones, namely the beam-column connection area, beams along the X direction of the plastic hinge, and beams along the Y direction of plastic hinge. The classification of beam-column connection specimens, namely Monolithic (SK-A0), and Non-monolithic with notches and support-plate (A1-B1). The damage specimen is examined visually with UPV to achieve the degree of damage in the main beam-column joint, the x-direction beam, and the y-direction in the plastic hinge area show in Fig. 1.

Fig. 1. Test location on reinforced concrete beam-column joints with UPV
5. Results

5.1 Visual Inspection

Results of visual inspection specimens of reinforced concrete beam-column joints damaged:

• SK.A0 Specimen
The SK.A0 specimen is a beam-column joint specimen that is made monolithically and has damaged after experiencing a peak load of 1.686 kg. A 5 cm x 5 cm grid specimen is made to facilitate visual observation. Visually damaged specimens have cracked on grid 2 with crack width of 1-2 mm, grid 4 with crack width <2 mm, and grid 6 with crack width < 2 mm. On the beam and column joints, cracks occur from the left to right side view with crack width > 2 mm. On the right side, a concrete cover was destroyed, and reinforcement was visible, the description seen in Fig. 2.

![Fig. 2. The Damaged Specimen of SK.A0.L1](image)

• A1.B1 Specimen
The A1.B1 specimen is a specimen beam-column joint that made non-monolithically with notch and pedestal plate strengthening and has damaged after having experienced a peak load of 1.662 kg. A 5 cm x 5 cm grid specimen is made to facilitate visual observation. Visually damaged specimens have cracked on grid 3 with crack width > 2 mm and grid 7 with crack width < 2 mm. In the beam and column junction, cracks occur from the left to right side view with crack width > 2 mm and cracks on the column surface, and on the right side, a concrete cover destroys on grid 1 to grid 2. On the right side looks a shattered concrete cover (Fig. 3).

![Fig. 3. The Damaged Specimen of A1.B1.L3](image)

5.2 NDT Inspection Using UPV

The UPV wave propagation test results for each section of the beam-column joints seen in Table 3.

| Name of Specimens | Location | Rec. Num | Column 200 x 200 mm | Beams 150 x 200 mm |
|-------------------|----------|----------|---------------------|-------------------|
|                   |          |          | transit time (μs) | width (mm) | P-Wave (m/s) | transit time (μs) | width (mm) | Wave (m/s) |
| SK.A0             | Joints   | 1        | 45.8               | 200          | 4258         |                |            |            |
|                   |          | 2        | 35.8               | 200          | 5447         |                |            |            |
|                   | Beam PH  | 3        |                    |              | 74.8         | 150            | 2607        |            |
|                   | Y-Direct | 4        | 120.8              | 150          | 1614         |                |            |            |
|                   |          | 5        | 62.8               | 150          | 3105         |                |            |            |
| Name of Specimens | Location  | Rec. Num | Column 200 x 200 mm | Beams 150 x 200 mm |
|-------------------|-----------|----------|---------------------|-------------------|
|                   |           |          | transit time (μs) | width (mm)  | P-Wave (m/s) | transit time (μs) | width (mm) | Wave (m/s) |
| Beam PH           | 6         |          | 120.8              | 200       | 2607        | 133.8              | 200       | 1614       |
| X-Direct          | 7         |          |                     |           |             |                     |           |             |
| A1.B1             | Joints    | 1        | 49.8               | 200       | 5221        |                     |           |             |
|                   |           | 2        | 47.8               | 200       | 5439        |                     |           |             |
| Beam PH           | 3         |          |                     |           |             | 155.8              | 150       | 1252       |
| Y-Direct          | 4         |          |                     |           |             | 67.8               | 150       | 2876       |
|                   | 5         |          |                     |           |             | 38.8               | 150       | 5026       |
| Beam PH           | 6         |          |                     |           |             | 116.8              | 200       | 2226       |
| X-Direct          |           |          |                     |           |             |                     |           |             |

### 5.3. Interpretation of results

To classify the level of damage, the authors propose a classification of concrete damage with the use of UPV and damage classification:

**SK.A0.** Beam-column joints SK.A0.L1 in the x-direction have an average P wave UPV of 2.05 km/s (very Poor) and an average P wave in the y-direction of 2.44 km/s (Poor) in the plastic hinge region. The concrete beam in the x-direction has a density (ρ) 1 gr/cm$^3$, CQD 18.25%, concrete strength of 2.6 MPa and static elastic modulus (Es) of 8.3 Gpa and dynamic elastic modulus (Ep) of 8.68 Gpa while in the y-direction density (ρ) 1.26 gr/cm$^3$, CQD 31.4%, concrete strength 3.91 Mpa and static elastic modulus (Es) 9.4 Gpa and dynamic elastic modulus (Ep) 12.35 Gpa. The Nakano classification is included in category 4 Spalling off of covering concrete (crack Width > 2 mm) then the cracked specimen is examined in detail by tapping the concrete blocks in x and y directions with the hammer on grid 1, and 2 and experience spalled concrete loose or unsound concrete so has to be removed, can be seen in Fig.4.

![Fig. 4. The specimen after knocked chek with the hammer](image)

**A1.B1.** The results of the UPV wave in the x-direction, the average P wave is 2.23 km/s (Poor), and the average P wave in the y-direction is 3.05 km/s (Questionable) in the beam of the plastic joint region. The concrete beam in the x-direction has a density (ρ) 1.12 gr/cm$^3$, CQD 24.2%, concrete strength 3.13 MPa, Es (8.7 GPa) and Ep (10.26 GPa) while in the y-direction density (ρ) 1.67 gr/cm$^3$, CQD 51.71%, concrete strength 7.32 MPa, Es (12.2 Gpa) and Ep (19.28 Gpa). The Nakano classification is included in category 4 Spalling off of covering concrete (crack width > 2 mm), cracked specimens are examined in detail by tapping concrete blocks x and y in direction with a hammer as high as 15cm and experiencing spalled concrete loose or unsound concrete so has to be removed, can be seen in Fig. 5.

![Fig. 5. The specimen after knocked chek with the hammer](image)
The relationship between UPV wave test with $\rho$ (density), $S_n$ (Strength of Concrete), Stiffness of concrete with $E_c$ (Static Modulus of elasticity) and $E_p$ (Dynamic Modulus of elasticity), CQD (Concrete Quality Designation) with damages classification for visual assessment of post Earthquake Damage Evaluation shows on Table 4.

| Range UPV Kms | Conc. Quality | $S_n$ Mpa | $E_c$ GPa | $E_p$ GPa | $\rho$ g/cm$^3$ | CQD | Damage Class |
|---------------|---------------|-----------|-----------|-----------|----------------|-----|--------------|
| >4.5          | Excellent     | >32.57    | >27.96    | >41.92    | >2.63         | >100|              |
| 3.6 - 4.5     | Good          | 12.89 - 32.57 | 16.07 - 27.96 | 26.83 - 41.92 | 2.03 - 2.63 | 70 - 100 | I             |
| 3.0 - 3.6     | Questionable  | 6.95 - 12.81 | 11.89 - 16.07 | 18.63 - 26.83 | 1.63 - 2.03 | 50 - 700 | II            |
| 2.1 - 3.0     | Poor          | 2.75 - 6.95 | 8.39 - 11.89 | 9.13 - 18.63 | 1.03 - 1.63 | 20 - 50 | III           |
| 1.8 - 2.1     | Very Poor     | 2.02 - 2.75 | 7.68 - 8.39 | 6.71 - 9.13 | 0.84 - 1.03 | 10 - 20 | IV            |
| <1.8          | Abnormal      | <2.02     | <7.68     | <6.71     | <0.84         | <10  |              |

6. Discussion

Many case studies on concrete structures indicate that the UPV analysis is suited to assess the degree of concrete damage. The findings, presented mainly in terms of UPV variations, help spot anomalies within a structure. When the building structure is damaged due to earthquake/overload, one of the quick ways to inspect the building is to classify each part of the structure visually. The use of UPV is faster, without damaging parts of the structure, and also induces damage to the core specimens as a result of the coring process, making it faster and more economical. The UPV test obtained density 0.84-1.03 g/cm$^3$, CQD 10%-20%, static elastic modulus 7.68-8.39 Gpa including very poor and visually is included in category IV spalling off of covering concrete (crack width > 2 mm)[3]. The use of UPV as supporting assessment for classification, repair, and maintenance of structures. If density, CQD, and elastic modulus of defining very poor classification, the structure that needs immediate repair.

7. Conclusion

The analysis of UPV and visual (rapid vulnerability assessment) to assess the structural condition of the beam-column joint. The study showed that the plastic hinge was more damaged than other parts of the beam-column joint and estimated the concrete quality. The use of UPV, along with the visual observations proposed here, provides additional information so that the lack of visual observations can complement the use of UPV for the inspection of concrete parts. The use of UPV wave interpretation (density, CQD, Strength & elastic modulus). Higher accuracy for estimating the concrete quality with higher accuracy. The use of UPV, along with the visual observations suggested here, offers additional details so that lack of visual observations can complement the use of UPV for the inspection of concrete parts.

Acknowledgements

The research was conducted at the Brawijaya University for a laboratory project with the BPPDN grant program and the research grant program of The Ministry of Research, Technology, and Higher Education of the Republic of Indonesia.

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