Energy dissipation of graded concrete beams on maximum reinforcement ratio

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Abstract. Energy dissipation is a parameter that contributes to the deformation process of structural elements. Factors affecting the value of energy dissipation include concrete compressive strength, reinforcement ratio, cross-sectional dimensions, and history of loading that occurs on the structure. In this study, the graded concrete (GC) beams with a maximum reinforcement design was tested under flexural test to analyse the resulting energy dissipation. The resulting data was then compared to the reference beams. The results showed that: 1) The use of cross-sectional dimension ratio of ½ in GC beams using maximum reinforcement can increase the energy dissipation by more than 2000%; 2) Design of reinforcement area should be based on the higher concrete strength to increase energy dissipation up to 100%; 3) The use of GC save on construction costs can increase energy dissipation by up to 400% with a reduction in load capacity of 25%; 4) The use of GC to improve the properties of structural elements can increase energy dissipation by more than 60% while increasing load performance by almost 50%.

1. Introduction

In terms of designing earthquake-resistant structural elements, structural engineers should ensure that the structure can perform in a ductile manner. Energy dissipation is a parameter that contributes to the deformation process of a structural element. The ductile deformation can be achieved through large energy dissipation. Energy dissipation is the ability of a structure to transmit energy through the process of yielding the reinforcement, so it determines the damage mechanism of the structures. Generally, the damage mechanism is exposed as structural cracks or yielding of reinforcement. Therefore, large dissipation energy is an ideal condition for structural elements. When the energy dissipation is large, plastic deformation can be performed before failure occurs. Park et al. [1] stated that energy dissipation is highly related to ductility. The resulting ductility is in a linear relationship to the energy dissipation. A structural element with a high ductility can withstand more loads due to large inelastic deformations before it reaches its failure.

Studies related to energy dissipation have been carried out by several researchers. Nao et al. [2] examined the effect of temperature on the resulting energy dissipation of concrete structures. The results show that an increase in temperature causes the resulting energy dissipation increase. In addition, the increase in energy dissipation is accompanied by an increase in the strain rate. Investigations related to the effect of lateral reinforcement in beam-column joints on energy dissipation have been carried out by Ugale et al. [3]. It was found that the energy dissipation of the...
beam-column connection increases when installed hoop reinforcement. The energy dissipation can be improved by adding restraints on a structural element. Priastiwi et al. [4] confirmed the application of confinement crossties can increase energy dissipation up to four times. On a structural level, Salazar [5] examined a portal with red brick walls. The red brick walls can increase the energy dissipation by 3.5 times compared to a portal without walls. Based on Hasan's research [6], an eccentrically braced steel frame system with the application of a wing-plate link and a hybrid link can increase the energy dissipation performance compared to the use of a built-up link. Furthermore, the energy dissipation is influenced by the compressive strength of concrete, the ratio of tensile fibre reinforcement, the ratio of compression fibre reinforcement, the cross-sectional dimensions and the history of loading that occurred in the structure.

In general, the energy dissipation can be determined from the definite integral of the load-deflection curve. Another method is to calculate the area under the load-deflection curve using a CAD-based program. This study aims to identify the structural characteristics of graded concrete (GC) beams with the use of maximum reinforcement focusing on the resulting energy dissipation. Material properties of graded concrete have been completely studied on previous studies [7–10]. The behaviour of reinforced concrete beam incorporating GC materials has been studied to understand the resulting load-deflection relationship, stress response, and the ductility [11–19]. The research finding is then used as reference materials and improvements for future research.

2. Experimental programme

2.1. Concrete mix proportion and specimen design

This research was conducted experimentally in the Laboratory of Structures, Universitas Negeri Malang. The concrete mixture used in this study consisted of two types of concrete strength, namely 20 MPa and 40 MPa. The concrete used was supplied concrete batching plant of PT. Tasa Beton. The consideration for the selection of ready mix concrete is that researchers want to create uniform concrete quality for all specimens. Concrete making on different batch resulted in uncontrolled quality on testing specimens. The specimen specifications are presented in Table 1, while the proportions of the concrete mixture are presented in Table 2. The Indonesian code [20] stipulates that the reinforcing steel used in the concrete structural elements is of the deformed type. However, this study used the plain type for all diameters for ease in the installation of strain gauges. Researchers also want to eliminate factors related to bond strength on different rebar diameter that commonly affected by different rebar types used during experimental testing.

Table 1. Specimen details

| Code | Beam dimension | Strength configuration (T-C side) (MPa) | Rebar ratio | Reinforcement details |
|------|----------------|----------------------------------------|-------------|-----------------------|
|      | Span (mm) | Width (mm) | Depth (mm) |                          |                         |
| G1/2 | 20 | 1,720 | 130 | 260 | 20-40 | 0.0159 |
| Code   | Beam dimension | Strength configuration (T-C side) (MPa) | Rebar ratio | Reinforcement details |
|--------|----------------|----------------------------------------|-------------|-----------------------|
| G1/2 40 | 1,720 130 260 | 20-40                                  | 0.0478      |                       |
| G2/3 20 | 1,400 130 195 | 20-40                                  | 0.0159      |                       |
| G2/3 40 | 1,400 130 195 | 20-40                                  | 0.0478      |                       |
| R1/2 20 | 1,720 130 260 | 20                                     | 0.0159      |                       |
| R2/3 20 | 1,720 130 260 | 20                                     | 0.0159      |                       |
Table 1. Specimen details (contd.)

| Code  | Beam dimension | Strength configuration (T-C side) (MPa) | Rebar ratio | Reinforcement details |
|-------|----------------|----------------------------------------|-------------|-----------------------|
|       | Span (mm) | Width (mm) | Depth (mm) |                         |                         |
| R1/2 40 | 1,400 | 130 | 195 | 40 | 0.0478 |
| R2/3 40 | 1,400 | 130 | 195 | 40 | 0.0478 |

Table 2. Concrete mix design per-cubic meter

| Concrete strength (MPa) | Water (kg) | PC (kg) | w/c (%) | Aggregate | Additive (kg) |
|-------------------------|------------|---------|---------|-----------|---------------|
| 20                      | 154        | 300     | 0.513   | 899       | 1030          | 1.04          |
| 40                      | 140        | 760     | 0.210   | 854       | 681           | 2.64          |

2.2. Specimen casting

Before specimen moulding, the formwork was laid on a flat surface and protected from weather exposure. The assembled reinforcement was placed on the formwork and ensures that the concrete cover is provided as planned by putting concrete blocks on some points. For GC beams, concrete moulding began by pouring a 20 MPa concrete mixture on the bottom of the mould until it reaches half of the beam depth. Compaction was carried out with a rubber mallet to ensure that the mass of concrete descends to the bottom, filling the gaps between reinforcement while removing air voids trapped in the moulded concrete. A 40 MPa concrete mix is poured over the previous layer until full. Mechanical compaction was continually applied until the air voids rise to the surface.

2.3. Specimen curing

Specimen curing was carried out for 28 days starting from the dismantling of the beam formwork. Curing was carried out by covering all parts of the reference specimens and the GC beams with wet burlap sacks. The humidity of the burlap sacks was always maintained by routinely wetting them with water. The purpose of this concrete curing is to prevent over evaporation of freshly harden concrete specimen which causes microcracks that can reduce the performance of the beam.

2.4. Specimen testings

The air-dried beam specimens were then cleaned and painted white. This painting aims to provide a clean surface that eases the researchers to observe cracks occurring during the test. The beams were then mounted on the loading frame positioning a concrete layer of 20 MPa at the bottom and 40 MPa at the top. The test setup was equipped with several instruments that aim to obtain data readings, including load cells, dial gauges, and data loggers. Loading was given manually using a hydraulic jack to maintain a load increment of 1 kN.
3. Results and discussion

3.1. Energy dissipation of specimens

Energy dissipation is obtained by calculating the area under the load-deflection curve from the experimental test. The load-deflection data series in spreadsheet format is imported into the CAD program. The area can be obtained by plotting the load-deflection curve using the polyline command, block area using the hatch command, and read the area information in the properties window. The area reading from P-Δ curve is shown in Figure 1 and the recapitulation are shown in Table 3.

![Figure 1. Calculation of energy dissipation](image)
3.2. Effects of cross-sectional dimension ratio on the energy dissipation of GC beams

Based on Table 4, if the energy dissipation is analysed based on the ratio of the cross-sectional dimension ratio, the percentage of energy dissipation of G1/2 40 increased by 2,484.64% when compared to G2/3 40. For G1/2 20, the value of the energy dissipation produced exceeds G2/3 20 of 2,142.89%. For the reference specimens, when R1/2 40 is compared to R2/3 40, the energy dissipation increases by 303.47%. An increase in energy dissipation is also shown by R1/2 20, where there is an increase of 2,490.59% when compared to R2/3 20. Park et al. [1] stated that the factor affecting the energy dissipation is the resulting ductility. A structural element that has a high ductility value will experience large inelastic deformations to withstand additional loads acting on the structure so that the structural element deforms in large deformation before reaching its collapse. A change in the cross-sectional dimension ratio from 2/3 to 1/2 can increase the energy dissipation performance by more than 2,000%. The increase in dissipation energy is also due to the beam with a cross-sectional ratio of 1/2 having a deeper ratio so that the crack propagation occurring in the cross-section is longer than in the 2/3. Therefore, the GC beam with a cross-sectional dimension ratio of 1/2 has better performance than 2/3. The increase in the resulting energy dissipation indicates that the structural elements can withstand earthquakes better through a gradual failure mechanism. The structural elements that adopting GC technology can be applied in earthquake-prone areas.

### Table 4. Effects of cross-sectional dimension ratio on the energy dissipation of GC beams

| Specimen types | Code  | Energy dissipation (kN.mm) | Significance (%) |
|----------------|-------|---------------------------|-----------------|
| GC beams       | G2/3 40 | 382.28                    |                 |
|                | G1/2 40 | 9,880.58                  | +2,484.64       |
|                | G2/3 20 | 220.73                    | +2,142.89       |
|                | G1/2 20 | 4,950.73                  |                 |
|                | R2/3 40 | 453.02                    |                 |
| Reference beams| R1/2 40 | 1,827.79                  | +303.47         |
|                | R2/3 20 | 235.69                    | +2,490.59       |
|                | R1/2 20 | 6,105.77                  |                 |

3.3. Effects of reinforcement area on the energy dissipation of GC beams

From the aspect of reinforcement area, G1/2 40 produces 99.58% greater energy dissipation than G1/2 40. The difference in energy dissipation of G2/3 40 to G2/3 20 is 73.19%. If the R1/2 40 is compared to R1/2 20, the resulting energy dissipation increases by 70.06%, whereas if R2/3 40 is compared to R2/3 20, the increase in energy dissipation is 87.12%. Research that focuses on reviewing the reinforcement ratio has been carried out by Sabelli et al. [21]. He showed that the addition of the reinforcement area causes greater resulting energy dissipation. A significant increase in energy dissipation is found in GC beams with a dimension ratio of 1/2. The use of higher strength concrete as a basis for calculating the reinforcement area increases energy dissipation by almost 100%. Analysis of energy dissipation due to varying reinforcement areas are shown in Table 5.

By using the same data provided in Table 5, it can be further analysed regarding the energy dissipation of the GC beam compared to the reference beam. The GC can be applied as a solution to reduce construction costs by replacing 50% of the volume of high-strength concrete in beams with a mixture of lower concrete strength. In this study, G1/2 40 is expected to replace R1/2 40 and G2/3 40 with...
can replace R2/3 40. In beams with a dimension ratio of 1/2, the use of GC can increase the energy dissipation by more than 400% despite a decrease load capacity of 25%. By using the same rebar configuration as the R1/2 40, the G1/2 40 can dissipate more energy but at a lower cost of implementation. Different patterns were found in beams with a dimension ratio of 2/3, therefore it requires further evaluation. The analysis of energy dissipation for cost-saving purpose is shown in Table 6.

Table 5. Effects of reinforcement area on the energy dissipation of GC beams

| Specimen types | Code  | Energy dissipation (kN.mm) | Significance (%) |
|----------------|-------|---------------------------|-----------------|
| GC beams       | G1/2 20 | 4,950.73                  | +99.58          |
|                | G1/2 40 | 9,880.58                  |                |
|                | G2/3 20 | 220.73                    | +73.19          |
|                | G2/3 40 | 382.28                    |                |
| Reference beams| R1/2 20 | 6,105.77                  | -70.06          |
|                | R1/2 40 | 1,827.79                  |                |
|                | R2/3 20 | 235.69                    |                |
|                | R2/3 40 | 453.02                    | +87.12          |

Table 6. Analysis of energy dissipation for cost-saving purpose

| Code  | Load (kN) | Energy dissipation (kN.mm) | Significance in: (%) | Load | Energy dissipation |
|-------|-----------|---------------------------|----------------------|------|-------------------|
| R1/2 40 | 159.2 | 1,827.7                  | -25.3                | 440.5 |                   |
| G1/2 40 | 118.9 | 9,880.5                  |                       |      |                   |
| R2/3 40 | 100.1 | 453.0                    |                      |      |                   |
| G2/3 40 | 78.19 | 382.2                    | -21.9                | -15.6 |                   |

In other cases, the GC can also be applied as an alternative to improve structural performance by replacing 50% of the volume of lower-strength concrete with the higher-strength concrete in the compression fibre and increasing the reinforcement area based on the higher-strength concrete. Improving the material properties of structural elements is an option for structural planners dealing with designing structural elements with strict and limited dimensions. For example, R1/2 20 is upgraded to G1/2 40 and R2/3 20 is upgraded to G2/3 40. The increase in beam properties allows the designer to maintain the same cross-sectional dimensions as the existing condition. This scenario can increase the energy dissipation in the range of 60% for both types of dimensional ratios. The most significant increase in capacity was found in the GC beams with a dimension ratio of 1/2, an increase in load was obtained by almost 50%. Further analysis can be seen in Table 7.

Table 7. Analysis of energy dissipation on properties improvement purpose

| Code  | Load (kN) | Energy dissipation (kN.mm) | Significance in: (%) | Load | Energy dissipation |
|-------|-----------|---------------------------|----------------------|------|-------------------|
| R1/2 20 | 79.8  | 6,105.7                   | 48.8                 | 61.8 |                   |
| G1/2 40 | 118.9 | 9,880.5                   |                      |      |                   |
| R2/3 20 | 64.0  | 235.6                     | 22.0                 | 62.1 |                   |
| G2/3 40 | 78.1  | 382.2                     |                      |      |                   |

4. Conclusion

- The use of cross-sectional dimension ratio of ½ in GC beams using maximum reinforcement can increase the energy dissipation by more than 2000%;
- Design of reinforcement area should be based on the higher concrete strength to increase energy dissipation up to 100%.
- The use of GC save on construction costs can increase energy dissipation by up to 400% with a reduction in load capacity of 25%.
- The use of GC to improve the properties of structural elements can increase energy dissipation by more than 60% while increasing load performance by almost 50%.
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