Numerical and experimental investigation on the shear resistance of functionally graded concrete (FGC) beams

M M A Pratama¹, W Arifanda¹, K Karyadi¹, N Nindyawati¹,
R Sulakstaningrum¹ and H Prayuda²

¹ Department of Civil Engineering, Faculty of Engineering, Universitas Negeri Malang, Indonesia
² Department of Civil Engineering, Faculty of Engineering, Universitas Muhammadiyah Yogyakarta, Indonesia

Abstract. Functionally graded concrete (FGC) is one of the most innovative materials combining two or more different concrete strength in building elements to optimise the construction cost. Studies focusing on the behaviour of graded concrete in flexural strength have been conducted by several researchers, whilst the research on the shear behaviour of FGC beam has not been initiated yet. Investigation on the shear behaviour of RC graded concrete beam is necessary due to the fabrication process could create a cold-joint that lower the load-carrying capacity of the element. Delamination possibly presents on the casted concrete layer during the loading and turns the beam behaviour more brittle in action. To further investigate these hypotheses, a laboratory testing and a numerical analysis are conducted in this research. Three pieces of RC beams with an identical dimension of 120 x 240 x 2200 mm are prepared with the concrete strength of 20 MPa, 30 MPa, and 20-30 MPa. The specimens are then tested using a four-point bending method in the age of 28 days. A set of strain gauge is mounted in stirrups surface to record the strain response on each incremental load. To validate the result, the specimens are also modelled in three-dimension using Abaqus. The results show that there is a significant difference in the stress-strain curve resulted from the experimental works and the model simulation. It is due to the limitation of programme to model the real interaction between the rebars and the concrete. In reality, the presence of aggregate interlocking, concrete contribution in withstanding compression stress, dowel effect improves the shear resistance of beams. Additionally, the interfacial failure did not present during the testing owing to the support of stirrups that confine the transition zone of concrete layers.

1. Introduction
Research related to functionally graded concrete (FGC) is continuing both in the material scope and its application to building elements. In previous research, investigations regarding the behaviour of FGC have been carried out and resulted in the finding that FGC can increase the rigidity of the material so as to increase the serviceability of structural elements. With the increased serviceability of the structure, the structure is able to undergo a minimum deflection as compared to structures composed of low strength concrete. The advantage of FGC is to reduce construction costs while still maintaining the level of serviceability. The FGC beams only require half the volume of high strength concrete and are combined with low strength concrete to produce serviceability that is identical with the beams composed
of fully high strength concrete. This scheme absolutely could save the use of cement as an expensive construction material that further optimizes the use of concrete in structural elements [1].

Preliminary research to investigate the compressive strength and modulus of elasticity of FGC has been carried out both experimentally and numerically [2-7]. Further, investigations regarding flexural behaviour that encompass the load-deflection, moment-curvature, stiffness, and ductility of FGC structures have been carried out through several research schemes. The results of the research show that the application of FGC to the structural beams can improve the performance of the structure, especially under flexural conditions [8-11].

The implementation of FGC casting is a crucial stage because the researchers should ensure that the transition of concrete layers bonded one another in creating a monolith structure. The provision of intensive mechanical compaction is carried out to accommodate these technical obstacles. Although the concrete layers transition has been eliminated through a compaction scheme, investigations regarding the shear resistance of the beam structure need to be studied to determine the shear behaviour of the beams in withstanding the working loads.

In this study, the authors intend to investigate further about the shear behaviour of FGC beams in withstanding the loads experimentally and validated using a finite element simulation program. FGC beams that have been designed are equipped with testing instruments to read shear strain during the testing. Beams with identical properties are also modelled in programme simulation and the resulting shear strain is compared with the experimental works. This research is expected to be able to complete studies related to FGC beams especially in terms of shear resistance, compared to conventional reinforced concrete beams.

2. Experimental programme

2.1. Specimens preparation

This research is split into two programmes, there were experimental study and finite element modelling. The laboratory testing was conducted at the Laboratory of Material Testing and Structure, Universitas Negeri Malang, Indonesia. The beams were modelled using Abaqus by inputting properties material obtained from the experimental test. Two groups of specimens were prepared, which were controlling specimens and testing specimens. The controlling specimens consisted of concrete cylindrical specimens for a compression test, rebars for tensile test, and conventional reinforced concrete (RC) beams for flexural test; meanwhile the testing specimens only consisted of FGC beams created from two layers of concrete mixes. The detail of specimens used in this research is shown in Table 1.

| Specimen Group | Notation | Description | Amount (pieces) |
|----------------|----------|-------------|-----------------|
| Controlling specimens | CA | Cylindrical concrete specimen 25 MPa | 3 |
| Cre | CB | Cylindrical concrete specimen 30 MPa | 3 |
| SM | Steel bars sample of longitudinal rebars | 3 |
| SV | Steel bars sample of stirrups | 3 |
| NA | Conventional RC beams 25 MPa | 2 |
| NB | Conventional RC beams 30 MPa | 2 |

| Testing specimens | GBA | Reinforced FGC beams with 2 layers configuration (30 – 25 MPa) | 2 |

2.2. Beam design

The beams were expected to undergo failure in flexure as the design of a/d = 3.04 which fulfill the range of 2,5 < a/d < 6.0. All of the RC beams were prepared to have 2200 mm in length and 120 mm x 240 mm for the cross-sectional dimension. The beams were doubly reinforced with 2D10 at the compression fibre and 2D10 at the tensile fibre as the longitudinal rebars. To record the reading strain of stirrups, a
A strain gauge was installed on the stirrups locating at 650 mm from the supports precisely at the mid-depth of the beams. The stirrups were d6-100 for supports and d6-175 in midspan. The reinforcement ratio used was 0.6% and concrete cover = 15 mm. The detail of beam design is shown in Figure 1.

3. Finite element modelling
The finite element modelling is intended to verify the findings on the experimental testing. The modelling was divided into 3 (three) phase, which was preprocessing, simulation, and post-processing. In the preprocessing stage, the data of concrete compression damage, concrete tension damage, and stress-strain relationship of concrete were input to the programme as material properties. The stress-strain relationship of steel is generated from experimental data, while the stress-strain of concrete is generated from CEB FIB 2010 based on the actual strength obtained from experimental testing in laboratory. In beam modelling, the beams were modelled in 3 dimensions using Abaqus. To model the graded structure, the beam is idealized into two layers of concrete with two different strength, which was 25 MPa and 30 MPa. The rebars were modelled as was applied in experimental testing. The interaction of intra-layers of concrete is set using tie to assure that the layers stay intact and were not slip during the bending; while the rebars – concrete were set to have a perfect bond. In simulation phase, the model is run using the parameter determined. The loading step used during the iteration is static, Riks. Maximum number of increments = 100; Arc-length increment = 10-15 to 1036. In post-processing, the resulting data from program simulation is analysed to generate the load-deflection relationship and the record of stirrups strain. Illustration of beam modelling in Abaqus is shown in Figure 2.

Figure 1. Beam design for the experimental programme
4. Results and discussion

4.1. Steel tensile strength

Two types of rebars were used in this research programme, which were 6 mm in diameter (plain) and 10 mm (deformed). For this test, three pieces of rebar samples were prepared for each rebar type. The universal tensile test was conducted using Universal Testing Machine (UTM). The resulting yield stress and ultimate stress of rebars are shown in Table 2. The result shows that the average yield stress of 6 mm rebars is 312.99 MPa, while the 10 mm is 345.55 MPa. Next, the average ultimate stress of 6 mm rebars is 418.31 MPa, while the 10 mm is 489.09 MPa.

| Specimens Notation | Yield stress (MPa) | Average yield stress (MPa) | Ultimate stress (MPa) | Average ultimate stress (MPa) |
|--------------------|--------------------|----------------------------|-----------------------|----------------------------|
| SV1                | 311.42             | 312.99                     | 425.98                | 418.31                     |
| SV2                | 311.42             |                            | 418.04                |                            |
| SV3                | 316.12             |                            | 410.90                |                            |
| SM1                | 334.04             | 345.55                     | 486.95                | 489.09                     |
| SM2                | 358.86             |                            | 496.11                |                            |
| SM3                | 343.77             |                            | 484.22                |                            |

4.2. Concrete compressive strength

The cylindrical concrete specimen size of 150 x 300 mm were tested to verify the actual concrete strength cast in RC beams. Three pieces of concrete specimens were tested for each of concrete strength at the age of 28 days using UTM. The result of the concrete compression test is shown in Table 3.

| Specimens Notation | Compressive strength (MPa) | Average compressive strength (MPa) |
|--------------------|-----------------------------|-----------------------------------|
| CA1                | 20.94                       | 24.55                             |
| CA2                | 26.47                       |                                   |
| CA3                | 26.25                       |                                   |
| CB1                | 37.17                       | 31.56                             |
| CB2                | 29.50                       |                                   |
| CB3                | 28.01                       |                                   |
The test showed that the actual strength of 25 MPa concrete specimens was 24.55 MPa, while the 30 MPa had actual strength of 31.56 MPa.

4.3. Load – midspan deflection
The flexural test on controlling beams and testing beams resulted in the load – midspan deflection graphs that are depicted in Figure 3 - 5. Figure 3 - 5 explains that all of the specimens of NA, NB, and GBA exhibited a similar achieving load – deflection in pre-cracked condition. It corresponded to the use of concrete strength that having small difference in strength; therefore, it resulted a similar trend. A noticeable contrast is found on the yield and ultimate condition which the NB withstanding a higher load capacity with less deflection on the elements. The contribution of higher concrete strength on the GBA was proven to reduce the resulting deflection by 14% and increase the load-carrying capacity by 5.07%.

![Figure 3. Load – mid-span deflection of NA](image1)

![Figure 4. Load – mid-span deflection of NB](image2)

![Figure 5. Load – mid-span deflection of GBA](image3)
4.4. Stress-strain response of stirrups

4.4.1. Experimental works. In experimental works, the strain was retrieved from the reading of strain gauge installed on the stirrups; while in programme simulation, the strain was generated from an element constructing the stirrups member. Figure 6 recaps the stress-strain relationship of the stirrups from experimental works. The resulting stress-strain graphs of each specimen’s variable exhibited a different characteristic from one to another. The NA resulted in a less steep curve as compared with the GBA and the NB. In higher stress points, the curves changed its pattern from linear to more fluctuated due to materials behaviour and numbers of technical issues. The strain gauge was suspected not installed correctly on the stirrups surface so it generated a bias data reading. To improve the strain reading during the testing, the preparation of stirrups surface should provide a smooth area for strain gauge to adhere perfectly until the testing ended. The adhesive compound should also maintain the flexibility of strain gauge while it provided a good stickiness between the strain gauge filaments and the contacting area. The use of small strain gauge, i.e. FLA 5-11, as testing device requires good preparation and maintenance due to its characteristics that are more sensitive to environmental condition and handling.

The fabrication and installation of rebars contributed to this result. During the fabrication process, the bending angle and parts length of steel bars were not uniform. It was expected that the assembling procedure could create a perfect spacing and a perfect bond between the longitudinal bars and the stirrups. In fact, it was indicated that some part of stirrups did not installed perfectly; resulting in a noticeable gap to the longitudinal bars. These findings, of course, interfered the obtaining strain data during the bending test. This gap would allow the stirrups to produce a high reading of strain in low loading attempt. In higher level of loading, the strain to stress pattern changed and indicated a strengthening behaviour regarding when the longitudinal bars reach and adhere the stirrups, it provided higher resisting respond of the stirrups during the loading. These findings are supported by the stress-strain data that changed from a leaning pattern to a steeper trend (Figure 6).

![Figure 6. Stress-strain relationship of NA, NB, and GBA from experimental test](image)

The respond of GBA in Figure 8 deviated from the controlling specimens. It was hypothetically due to the placement of the strain gauge device at the transition area of the higher concrete strength mix and the lower concrete strength mix; and the loading scheme that was not symmetrical. The asymmetric loading procedure leads the beam to deflect more at one side of beams resulting the strain gauge
positioned at the other side underwent less response of strain at high increment of loading. This consideration is supported by the condition of beams after conducting a bending test (Figure 7). Figure 7 shows that the beams deflected more on the left side and created large crack opening than the other side. In this case, the strain gauge was installed in the right side which was affected by small deflection so the less strain reading at that part. From Figure 7, it is observed that the interfacial failure that is predicted does not present. It was due to the support of stirrups to maintain the bond and the compacting procedure during the concrete making is robust in creating a good adhesiveness between the concrete layers.

Figure 7. Asymmetrical beam deflection after bending test

4.4.2. Programme simulation. Figure 8 shows a stress-strain relationship of stirrups of NA, NB, and GBA from programme simulation. A different pattern of the graph is observed from this data to the experimental works. All of stirrups were in elastic condition indicated from the resulting stress that below the yield stress. All of the beams followed a linear pattern in the stress-strain relationship. By using identical configuration rebars, the higher concrete strength helps the stirrups to withstand less strain the beams composed of the lower concrete strength. Interestingly, the stress-strain relationship of the GBA was in between the NA and the NB; and followed the inclination of the NA the most than the NB. It shows that the presence of higher concrete strength mix could improve the structural performance of beam and replicate the behaviour of normal beam composed of fully high strength concrete mix. This scheme will reduce the construction cost while still maintaining the structural performance.

The comparison of strain – strain relationship obtained from experimental testing and programme simulation are displayed in Figure 9 – 11. Figure 9 – 11 show that there are several differences in the pattern observed from the graph. The resulting graph from experimental data rather fluctuates than the programme simulation results. It is due to the limitation of programme to model the real interaction between the rebars and the concrete. In reality, the presence of aggregate interlocking, concrete contribution in withstanding compression stress, dowel effect improves the shear resistance of beams. These factors could be mimicked by programme modelling.

5. Conclusion
- In experimental works, the stress-strain curves changed its pattern from linear to more fluctuated due to materials behaviour and numbers of technical issues. The strain gauge was suspected not installed correctly on the stirrups surface so it generated a bias data reading.
- The gap between stirrups and longitudinal bars allow the data to produce a high reading of strain in low loading attempt. In higher level of loading, the strain to stress pattern changed and indicated a strengthening behaviour regarding when the longitudinal bars reach and adhere the stirrups, it provided higher resisting respond of the stirrups during the loading.
- The asymmetric loading procedure leads the beam to deflect more at one side of beams resulting the strain gauge positioned at the other side underwent less response of strain at high increment of loading.
It is observed that the interfacial failure that is predicted does not present. It was due to the support of stirrups to maintain the bond and the compacting procedure during the concrete making is robust in creating a good adhesiveness between the concrete layers.

The resulting graph from experimental data rather fluctuates than the programme simulation results. It is due to the limitation of programme to model the real interaction between the rebars and the concrete. In reality, the presence of aggregate interlocking, concrete contribution in withstanding compression stress, dowel effect improves the shear resistance of beams.

**Figure 8.** Stress-strain relationship of NA, NB, and GBA from programme simulation

**Figure 9.** Stress-strain relationship of NA

**Figure 10.** Stress-strain relationship of NB

**Figure 11.** Stress-strain relationship of GBA
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