Seismic performance of low-rise building using graded concrete as flexural elements

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Abstract. Graded concrete is a material innovation in the field of civil engineering that aims to create environmentally friendly and economical construction materials. Previous research has shown that graded concrete increases material rigidity so that graded concrete can increase the level of serviceability of structures, indicated by the decreasing of deflection. Investigations on the performance of structures using graded concrete as building material need to be studied further with broader structural indicators. Further studies related to structural performance including base shear reactions, fundamental periods, storey stiffness, storey drift, and storey displacement, should also be discussed. In this study, a 3-storey residential building is modelled using ETABS in 3D approach. The effect of disparity in concrete strength on structural performance is examined. The buildings that employ graded concrete as a construction material can offer a better level of occupant comfort due to the lesser vibration period generated. The application of graded concrete in beam components can increase the value of the storey stiffness. It is because of the greater the modulus of elasticity, the greater the stiffness produced by the beam. It increases the confinement of the enclosed plate so that the stiffness of the building floor also increases. The use of high strength concrete in the beams will change the mode shape of the structure from flexure to shear type. In shear mode shape, the column will form a double curvature so that the mode shape of the structure tends to form a convex pattern. The benefit of the shear-type mode shape is the lesser value of storey displacement at the top level.

1. Background

Intensive research of graded concrete as a construction material was originally inspired by the study in metallurgy that combines metal and ceramics to form the outer shell of a space shuttle that is heat-resistant while still providing good comfort for passengers [1]. Graded concrete is a material innovation in the field of civil engineering that aims to create environmentally friendly and economical construction materials [2]. The development of graded concrete can be done with 2 (two) approaches, which are by using additional materials apart from the main material in the concrete mix, such as fibres; or by modifying the proportions and the properties of the concrete constituents. The main difficulty in incorporating fibres in concrete is the risk of clumping so that the fibres being not evenly distributed to the moulded elements [3]. Other reference stated that fibrous concrete requires a higher amount of water-to-cement factor so the concrete will undergo the decrease of resulting strength [4]. Recent studies
demonstrated that graded concrete could be created by modifying the proportion of concrete constituents. The approach is carried out in 2 (two) ways, which are: 1) by arranging the coarse aggregates to have varying percentages gradually by the function of element depth; or 2) by preparing multiple batches of concrete mixes with different strength, then layer the concrete mix alternately, and applying intensive compaction scenario to make a smooth strength gradation along with the element’s depth. Previous research has shown that graded concrete possibly increases material rigidity so that graded concrete can increase the level of serviceability of structures, indicated by the decreasing of deflection. The increase in stiffness is caused by the increasing modulus of elasticity [5–15].

Research on graded concrete in structural scope has been carried out by researchers both experimentally and using finite element simulation. Previous research has modelled a two-story building that applied the graded concrete material on beam elements [6]. The results showed that the use of graded concrete as part of structural components can reduce the deflection and optimise the use of reinforcing steels. Investigations on the performance of structures using graded concrete as building material need to be studied further with broader structural indicators. Previous research has only focused on reviewing deflections that occur in beam elements and analysis of reinforcement area. Further studies related to structural performance including base shear reactions, fundamental periods, storey stiffness, storey drift, and storey displacement, should be discussed. In this study, a 3-storey residential building is modelled using ETABS in 3D approach. The effect of disparity in concrete strength on structural performance is examined. This research is expected to provide an overview of the feasibility of application of graded concrete in a multi-storey building.

2. Seismic Loads
In terms of the tectonic conditions, Indonesia is located at the intersection of the world's large plates and several small plates which cause the potential of multiple earthquake experience. Indonesia is surrounded by four main plates, namely the Eurasian Plate, the Indo-Australian Plate, the Philippine Sea Plate, and the Pacific Plate, while the small plates consist of Burma, Sunda, the Sea of Banda, the Sea of Maluku, Timor, the Head of the Bird, Maoke, and Woodlark. The active subduction zones in the West to the Eastern part of Indonesia are identified as the cause of the earthquake in Indonesia [16]. In the western part of Indonesia, the process of inducing the Indo-Australia plate into the Eurasia plate in Western Sumatera resulted in an earthquake with a magnitude of 8 to 9, as happened in Aceh in 2005. It was considered the worst natural disaster and affected 14 countries and caused economic losses of up to 10 billion USD. The significant earthquakes in Sumatera are dominated by earthquakes with a thrust mechanism that occurs as a result of the subduction process and several shear faults. Numerous active faults in Sumatera has been updated in the provision into 43 segments [17-18]. The updated earthquake mapping in Indonesia is displayed in Figure 1.

To analyse the performance of a building against earthquake loads, an earthquake data input is required to represent the lateral load acting on the building, such as a time history record which is a recording of real earthquake events. Unfortunately, this data is not available in all regions. The earthquake modelling that is only based on maximum ground acceleration, is not appropriate because the response of the structure depends on the frequency of ground motion which is a function of time. To overcome this problem, earthquake load can be modelled using a spectrum response, which provides the relationship between the vibration period to the spectral acceleration [19].

Based on Figure 1, the spectral acceleration 0.2 second is 1.4g, while the spectral acceleration 1.0 second is 1.8g. The building is planned as a residence, so it has a priority factor (Ie) = 1.0. The building is considered located at site class D. The amplification factor of the short period earthquake Fa = 1.0, while the amplification factor of the earthquake acceleration period 1.0 second Fv = 1.5. Calculations are carried out to generate spectral acceleration according to the period. The response spectrum curve used in this analysis is shown in Figure 2.
Figure 1. (a) Spectral acceleration 0.2 second with damping = 5% for probability = 2% in 50 years; (b) Spectral acceleration 1.0 second with damping = 5% for probability = 2% in 50 years
3. Method

This research was conducted in a program simulation, ETABS. A three-story is modelled in 3D. The building is designed with bay width = 4 meters and inter-storey height = 3.5 meters. The building functions as a residence with a live load of 1.92 kN m\(^{-2}\). All structural elements have been assigned with a moment of inertia modifier to accommodate a cracked section consideration due to loading. The dimensions of the building structural elements are written in Table 1. The illustration of the building model is shown in Figure 3. The building model is then applied to several concrete strengths as a testing variable. The concrete strength is applied to the beam elements, while the plates and columns follow the lowest strength of graded concrete proportion. In this research, the material properties are referred to Pratama [15]. The properties of materials used in this modelling are divided into 2 (two) categories, which are normal concrete (denoted with U) and the graded concrete (denoted with G). For instance, U30 is normal concrete designed with 30 MPa in compressive strength. Whilst G30-40 is graded concrete made of concrete mixes of 30 MPa and 40 MPa. The list of concrete strength and modulus of elasticity is shown in Table 2.

**Table 1. Dimensions of the building structural elements**

| Element(s) | Code | Dimension (mm) |
|------------|------|----------------|
| Columns    | C    | 500 x 500      |
| Tie Beams  | S    | 200 x 400      |
| Beams      | B    | 300 x 400      |
| Plate      | P    | 120            |

**Table 2. Concrete strength and modulus of elasticity for modelling [15]**

| Code  | Concrete strength (MPa) | Modulus of elasticity (MPa) | Sig. (%) |
|-------|-------------------------|-----------------------------|----------|
| U30   | 34.35                   | 35,714.30                   |          |
| U40   | 46.81                   | 44,444.40                   |          |
| U50   | 56.99                   | 55,555.60                   |          |
| G30-40| 35.12                   | 40,000                      | +12.00   |
| G30-50| 36.36                   | 40,816                      | +14.28   |
| G40-50| 49.07                   | 50,000                      | +12.50   |
4. Results and discussion

4.1. Base Shear Reaction
Base shear is a reaction occurring at the base of a building due to the load combination acting on the structure, including dead load, live load, and earthquake load. The base shear reaction is generated computationally after the simulation completed. The base shear for each type of building is shown in Table 3. Table 3 shows that all buildings have the same value of base shear whether in the X-direction and Y-direction. It is because the building model has symmetrical geometry on both sides so that the seismic load acting in the x and y directions result in the similar magnitude of the reaction.

| Concrete Strength | X-Direction (N) | Y-Direction (N) | Significance (%) |
|-------------------|-----------------|-----------------|------------------|
| U30               | 300219.43       | 300219.43       |                  |
| U30/40            | 311497.75       | 311497.75       | +3.76            |
| U30/50            | 313479.86       | 313479.86       | +4.42            |
| U40               | 330440.88       | 330440.88       |                  |
| U40/50            | 341186.8        | 341186.8        | +3.25            |
| U50               | 348132.94       | 348132.94       |                  |

In buildings with normal concrete (indicated with U code), the higher the strength of the concrete, the greater the shear force exhibited. This is due to the greater concrete strength produce in the greater structural rigidity so that the building base produces a higher restraint [20]. This condition allows the building to produce a greater reaction as the idealization of the fixed supports which are stiffer than the hinge supports. In buildings with graded concrete materials (indicated with G code), the value of base shear forces generated by the models is between the responses of buildings that are formed from of the concrete strength constituents. For example, a U30/50 building in which building beam elements are arranged with 30 MPa and 50 MPa graded concrete, while columns and plates are composed of 30 MPa quality concrete, results in a base shear force reaction of magnitude between those exhibited in U30 and U50. The use of two concrete strength that has a modulus of elasticity difference of 14.28% can increase the base shear by 4.42%.

4.2. Fundamental Period
The fundamental period is the time needed by the structure to perform a certain mode shape. The magnitude of the fundamental period is influenced by several factors, among which are the stiffness of the structure, the weight of the structure, the height of the structure, the orientation of the placement of the geometry of the column, the presence of walls in the structure, and the effect of the cross-section. In this case, the factor influencing is structural stiffness and structure weight [21].

The greater the concrete strength in buildings, the structural rigidity and the weight of the structure will linearly increase. Increasing the stiffness of the structure will impact on the reduction in the natural period of the building. It is confirmed by the equation which states the magnitude of the natural period is always inversely proportional to the rigidity of the structure. The theory is proven in this study which shows that the G30/50 building has a shorter period compared to U30. The buildings that employ graded concrete can offer a better level of occupant comfort because with the greater value of the vibrational period, the structure experiences shaking in a longer time. This effect will be pronounced when a strong earthquake occurs so that buildings made of the low concrete strength being at the risk of exceeding the elastic phase due to a large shake.

In this study, the specific gravity of concrete for each strength is considered constant, while it is a function of cement fraction in the concrete mixture. The higher the concrete strength, the content of cement increase, and it arises the specific gravity of concrete. The specific gravity of concrete determines the weight of the structure. As a result, the greater the weight of the structure, the greater the
natural period value exhibits. It is a reason for the development of lighter construction material for the multi-storey buildings. The natural period of each structure in Mode 1 is shown in Table 4. The mode shape of Mode 1 on the overall building models is shown in Figure 4.

**Table 4.** The natural period of structures

| Mode  | Fundamental Natural Period (s) |
|-------|-------------------------------|
|       | U30  | U30/40 | U30/50 | U40  | U40/50 | U50  |
| 1     | 0.418 | 0.405  | 0.402  | 0.374 | 0.362  | 0.335 |
| Sig. (%) | -3.11 | -3.83  | -3.21  |

**Figure 4.** Typical mode 1 shape of 3-storey building

4.3. **Storey Stiffness**

Slabs and beams in reinforced concrete structures are monolithic. It is due to the concrete formwork and the concrete placing being carried out simultaneously. In the analysis, the calculation of the beam capacity also takes into account part of the effective width of the slabs as part of the beam section. The slabs component can indirectly increase the flexural capacity of the beam. Even though the building floor is composed of beams and slabs members, the components contributing to the storey stiffness are not limited to those elements. The presence of the column and the compressive axial forces working at the columns can increase the storey stiffness of a building [22]. With a typical floor plan from the ground to the top floor, the greater the effect of the confinement given by the columns to the storey, the storey stiffness will increase. This is per the analysis results which shows that the storey located at the base has a greater value of stiffness than the top floors. The higher the elevation of the storey being observed, the stiffness value decrease along with the reduction of the confinement effect given by the columns.
The application of graded concrete in beam components of G30/40, G30/50, and G40/50 building can increase the value of the storey stiffness compared to U30 and U40. It is because of the greater the modulus of elasticity of the material used in the beam components, the greater the stiffness produced by the beam. It increases the confinement of the enclosed plate so that the stiffness of the building floor also increases. The results of the storey stiffness in each building type are shown in Figure 5.

4.4. Storey Drift

Storey drift is the value of relative shift occurring on each floor against the floor below it. Based on Figure 5, the higher the floor elevation towards the ground, the story drift value is increasing. The increase of the difference in storey drift values occurs between elevations +1.2 to +4.7, and gradually decreases as occurs at elevations +4.7 towards +8.2 and +11.7 meters. A multi-storey building could be idealised as a single cantilever beam that is fixed supported on the ground. The existence of seismic loads working in the lateral direction of the building act as a shear force on the beam which causes the structure to experience sway. Gravitational loads on buildings, such as dead loads, additional dead loads, and live loads work as if they were axial forces on a cantilever beam. Both of these loads, both the earthquake loads and the gravity loads, cause the structure to experience a large lateral displacement at the middle level and a minimum value at the lower and upper levels. The minimum value of displacement occurring at the top level is logically due to the absence of a working live load, while the large value of displacement in the middle-level area is caused by the accumulation of gravitational loads along with the earthquake. In detail, the storey drift values and pattern are shown in Figure 6.

Based on Figure 5, the greater the concrete strength, the building will not drift at the great magnitude. Figure 5 shows that the U50 exhibits the lowest value of storey drift than the U30, where the structure experiences the greatest drift compared to other models. The lower the strength of concrete in a building, it will affect the comfort factor of the occupants because the storey drift due to the earthquake is very significant [23]. The storey drift patterns occurring in the G30/50 and the G30/40 models appear to coincide and are between the U30 and U40 curves, while the G40/50 appear to have a more upright curvature and are between U50 and U40. When examined further by taking into account the compressive strength data of G30/50 and G30/40, both concrete materials have the resulting compressive strength and modulus of elasticity that only slightly different to U30, so that the structure behaves similarly with U30. The G30/50 creates a curve with a lesser curvature. If the storey drift aspect is taken into consideration by engineers, it is recommended to use G40/50 instead of G30/50 and G30/40 due to the magnitude of storey drift.
Figure 6. Storey drift

4.5. Storey Displacements

Storey displacement in buildings is influenced by the bending stiffness of the beam against the columns, and the support conditions in the structural model [24]. The use of high strength concrete in the beams will change the mode shape of the structure from flexure to shear type. In shear mode shape, the column will form a double curvature so that the mode shape of the structure tends to form a convex pattern. This can be noted that the storey displacement pattern of the G40/50 is more convex compared to the G30/40 and the G30/50, which tends to shape in a straight pattern. This benefit of the shear-type mode shape is the lesser value of storey displacement at the top level.

The use of fixed support at the base of the building model represents footing behaviour of the actual building. The support type will determine the overall structural behaviour of the building. Fixed support will prevent a large displacement value on the lower floors. The structure will display the mode shape in flexure type in the middle and bottom structure, and the shear-type in the middle to the top to create a more stable structure. The value of storey displacement and its graph are shown in Figure 7.

Figure 7. Story displacement
5. Conclusion
The value of base shear reaction generated on the graded concrete building is between the responses of buildings that are formed from the concrete strength constituents. The higher the strength of the concrete, the greater the shear force exhibited. The increase of the material stiffness will impact on the reduction in the natural period of the building. The buildings that employ graded concrete as a construction material can offer a better level of occupant comfort due to the lesser vibration period generated. The application of graded concrete in beam components can increase the value of the storey stiffness. It is because of the greater the modulus of elasticity of the material used in the beam components, the greater the stiffness produced by the beam. It increases the confinement of the enclosed plate so that the stiffness of the building floor also increases. The use of high-strength concrete in the beams will change the mode shape of the structure from flexure to shear type. In shear mode shape, the column will form a double curvature so that the mode shape of the structure tends to form a convex pattern. The benefit of the shear-type mode shape is the lesser value of storey displacement at the top level.

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