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MOMENT-CURVATURE ANALYSIS OF GRADED CONCRETE BEAM WITH CONCRETE STRENGTH DISPARITY VARIATIONS

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Abstract

The application of graded concrete on structural elements is predicted to increase the capacity of the structural performance, serviceability, and to reduce costs compared to conventional concrete structures. This study aims to analyze (1) the load-deflection relationship, (2) the moment-curvature, (3) the deflection ductility ratio, and (4) the crack pattern. This study used reinforced concrete (RC) beams specimens with the dimension of 13x19x150 cm which was categorized as reference specimens and graded concrete beams. For reference specimens, an RC beam possessing concrete strength of 30 MPa; 40 MPa; 50 MPa were prepared; For the graded concrete beams, two specimens made of 30-40 MPa; 30-50 MPa; 40-50 MPa were prepared. In terms of casting graded concrete beams, low-strength concrete is placed on the tensile fiber of the beam, while on the compressive fiber of the beam, high-strength concrete is placed. The specimens were tested using the four-point bending method. The results showed that the increase in the concrete strength in the compression fiber of the beam contributed to the increase in load capacity, stiffness, and serviceability in the post-crack phase. The increase of concrete strength in compression fibers by 20 MPa is considered effective and has a positive impact on the moment-curvature capacity and is considered efficient in construction costs. The deflection ductility of the beam is classified as partial ductile and is adequate for structural design in earthquake-prone areas. A flexural cracks pattern was found on each specimen.

Keywords: Moment capacity, Curvature, RC beams, Graded concrete

Introduction

Reinforced concrete beams are structural elements formed from concrete and reinforcing steel which have different material characteristics (Laboratorium Rekayasa Struktur Institut Teknologi Bandung, 2013). Reinforce concrete beams are designed to provide resistance against flexure, shear, torsion, fatigue, impact, and blast loading. The load capacity of concrete structures is affected by the cracking behavior of concrete (Siddika et al., 2019; Slowik, 2019; Mangalathu, 2018; Daugevičius et al., 2019). Concrete is a brittle material and has a low modulus of elasticity. Due to excessive loading, the concrete will experience micro to macro cracks which can significantly reduce the stiffness of the structural elements. This is reinforced by the statement (Yu et al., 2021) which states that concrete will experience complex behavior under high levels of loading, this is inversely proportional to the fact that the concrete is subjected to a static load. Various researches demonstrate that deflection development and reached yielding depend on the reinforcement (steel) ratio (Valivonis et al., 2010; Hawileh, 2012). This may be related to the exploitation of the compressed concrete. If the reinforcement ratio is low, the exploitation of the compressed concrete is also greatly reduced until the yielding of reinforcement is reached. Therefore, the deflection (when the yielding of reinforcement is reached) of the strengthened beams with a low reinforcement ratio is the biggest. This is due to the unexploited deformability of the compressed concrete (Daugevičius et al., 2019). To overcome this, steel reinforcement is needed to assist the structure in maintaining its strength and stiffness during loading before failure occurs. In addition to the stiffness aspect, ductility studies are needed to find out more about the behavior of the structure from the occurrence of yielding in the flexural reinforcement to the collapse of the structural elements. The analysis can be carried out using the moment-curvature relationship data, which can be processed from the load-deflection relationship data (Gang-Kyu et al., 2017).

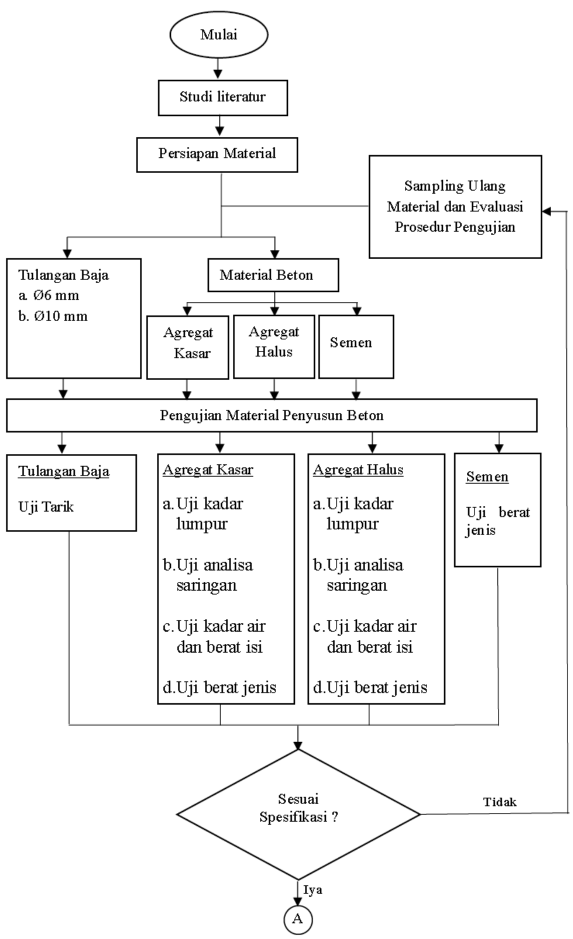
Moment-curvature is a graph that shows the magnitude of the rotational value of a stretch of reinforced concrete beam when it receives a bending moment. The flexural behaviour is an important part of the problem, and it can be characterised through the equivalent plastic hinge length and the Moment-Curvature law of the fixed end (Gentile et al., 2018). The moment-curvature graph displays the magnitude of the bending moment and the magnitude of the rotation that occurs (Laboratorium Rekayasa Struktur Institut Teknologi Bandung, 2013). When a reinforced concrete beam is given a working load in the form of bending moment, the beam will form a moment-curvature graph in the form of a trilinear graph. In the first phase, the concrete experienced the first crack in the tensile fiber section due to a moment of 12% of the working ultimate moment. The second phase is the yield phase of the tensile steel reinforcement due to crack propagation and distribution to the tensile reinforcement. The third phase is the phase where the concrete beam collapses due to the ultimate moment and cracks from the tensile fibers that propagate to the compression fiber of the concrete beam (Satiadi et al., 2016). Therefore, reinforced concrete beams must be designed with sufficient deflection ductility values so as to increase the serviceability to withstand bending moments with small deflection values. The small deflection will affect the radius of curvature of the beam (Karolina, 2008).

Deflection in reinforced concrete beams is closely related to the serviceability of the beam in receiving loads. Ductility in concrete may be related to the fact that bond cracks may not form at the same time as mortar cracks. This time lag affects the deformation capability of concrete before failure (Mansor et al., 2020). In structural members, the ductility refers to the ability of undergoing large deformations after the yielding of tensile reinforcement. This may save lives by giving warning of failure and preventing total collapse (Reddy & Rao, 2012; Cinitha et al., 2014). Aylie et al., (2015) suggested that in order to increase the serviceability of the beam, the graded concrete method could be applied. Based on the results of the simulation program carried out in this study, it is known that the stiffness of the graded concrete beam material is almost equivalent to the stiffness of a conventional concrete beam. Then, Pratama et al., (2019) conducted research on the modulus of elasticity in graded concrete using the Strand7 program, from the modeling and analysis process, the results showed that graded concrete could increase the modulus of elasticity up to 37% compared to beams of uniform quality. Therefore, the application of graded concrete on structural elements can reduce the value of the deflection and increase the serviceability.

Research on graded concrete as a beam element has been carried out intensively in a series of previous studies. However, this research still uses a combination of 2 (two) different concrete qualities and the research is still based on numerical. Previous research conducted by Pratama, Suhud et al., (2019) regarding the analysis of finite element bending moment-curvature in graded concrete beams, it shows that an increase in structural stiffness of 4.7% has the implication of reducing the deflection value of the beam when subjected to a working load. To complete the series of studies that have been carried out previously, validation is needed with similar research through an experimental-based approach.

Research Methods

The stages of experimental research regarding the moment-curvature of graded concrete beams with variations in concrete quality are shown in Figure 1.



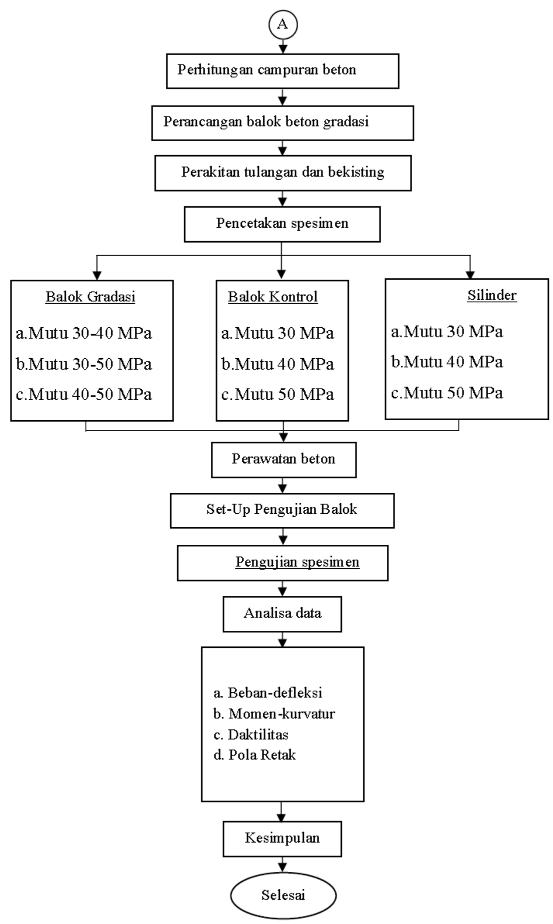


Figure 1. Research Outline

Specimen testing was carried out at the Structural Laboratory of the State University of Malang. Experimental specimens made in the form of reinforced beams with dimensions of 13x19x150 cm with a quality of 30 MPa, 40 MPa, and 50 MPa as control beams and a grading beam with a quality of 30-40 MPa, 30-50 MPa, and 40-50 MPa each totaling 2 specimens. The loading method used is four-point bending and the beam is given a simple support. The concrete cylinder specimens observed were concrete cylinders with dimensions of 15 cm with a height of 30 cm and variations in quality of 30 MPa, 40 MPa, and 50 MPa with 6 units of each quality and tested for compressive strength at the age of 28 days. Concrete steel reinforcement specimens used 6 mm for stirrup reinforcement and 10 mm for main reinforcement. Both reinforcement specimens were not turned and tested for tensile strength using the Universal Testing Machine (UTM). Details of reinforcement on the test object are presented in Figure 2 and the test set-up design is shown in Figure 3.

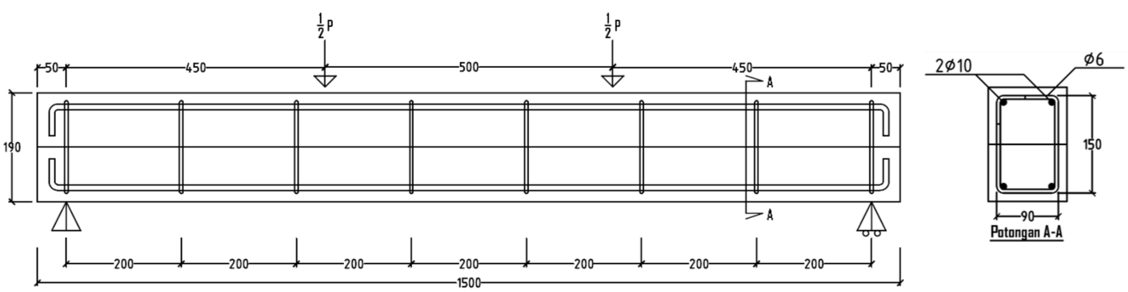


Figure 2. Details of Test Object Reinforcement

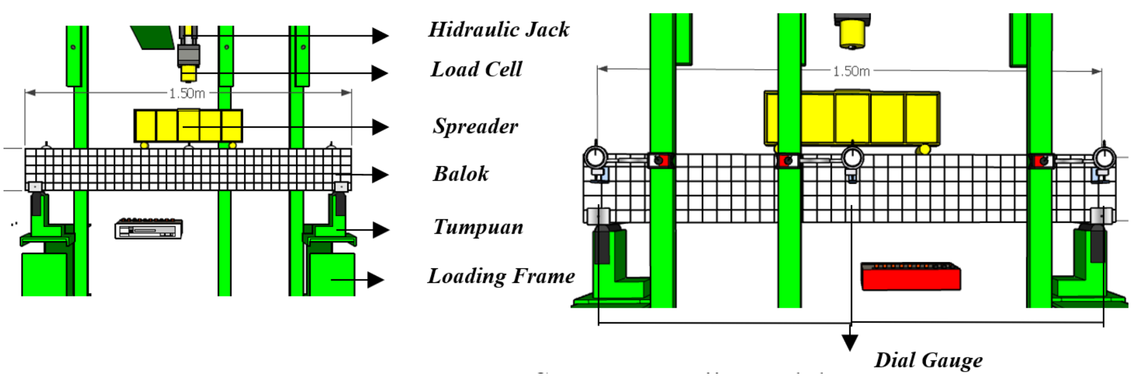


Figure 3. Beam Test Set-Up

Results and Discussion

Concrete Mixture Ratio

The planning and calculation of the concrete mixture in this experimental study used the reference of SNI 03-2834-2000 with the design concrete quality of 30 MPa, 40 MPa, and 50 MPa. Based on the material testing data that has been carried out previously, a recapitulation of material requirements is obtained as presented in Table 1.

Mutu Beton	Semen	Air	Agregat Halus	Agregat Kasar
30 MPa	1	0.67	1.78	1.85
40 MPa	1	0.55	1.42	1.47
50 MPa	1	0.45	1.09	1.31

Compressive Strength Characteristics of Concrete

A recapitulation of the achievement of the compressive strength of concrete at each quality was obtained from the specimens which had uniform compressive strength characteristics. The compressive strength is obtained through testing using the Universal Testing Machine (UTM) with reference to SNI 1974-2011. The entire compressive surface of the test object is not coated with sulfur capping in order to determine the capacity of the existing compressive strength and the natural crack pattern formed on the test object. The recapitulation of the compressive strength of concrete is shown in Table 2.

Table 2. Recap of Concrete Compressive Strength Results

Kode Benda Uji	Sampel	Berat benda uji	Beban maks	Diameter Penampang (d)	Luas Penampang (A)	Kuat Tekan (σ)	Kuat Tekan Rerata
		(kg)	(kN)	(mm)	(mm²)	(MPa)	(MPa)
	1	11,7	478,7	150	17671,46	27,09	
C 30	2	11,7	489,2	151	17907,86	27,32	27,18
	3	11,7	486,1	151	17907,86	27,14	
	1	11,8	708,4	150	17671,46	40,09	
C 40	2	11,9	719,1	151	17907,86	40,16	40,54
	3	11,9	731,2	150	17671,46	41,38	
	1	11,9	821,4	150	17671,46	46,48	
C 50	2	12	904,1	150	17671,46	51,16	49,47
	3	12,1	897,3	150	17671,46	50,78	

Reinforcement Tensile Strength

Specifications for steel reinforcement specimens in the tensile strength test are prepared in accordance with SNI 2052-2014. Tensile strength testing procedures and procedures for data processing test results refer to SNI 07-2529-1991. Based on the results of the material testing that has been carried out, the material properties of steel reinforcement are obtained which are summarized in Figure 4.

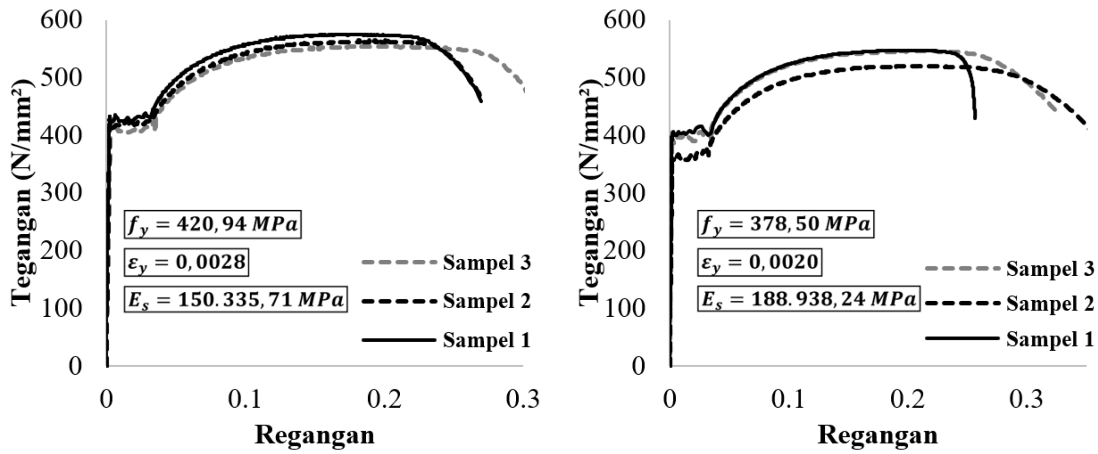


Figure 4. Stress-Strain of Steel Reinforcement (a) Ø6 ; (a) Ø10

Load-Deflection Achievement

From the flexural test, the load and deflection data of the beam can be obtained which can then be analyzed at 3 (three) important points, namely the first crack, yield steel, and the ultimate. The configuration of the quality of the concrete in compression fiber and tensile fiber in each specimen produces different load and deflection performance patterns. The data recapitulation of the bending test results on the control beam (BK) and the gradation beam (BG), is presented in Figure 5 for load performance and Figure 6 for deflection performance, respectively
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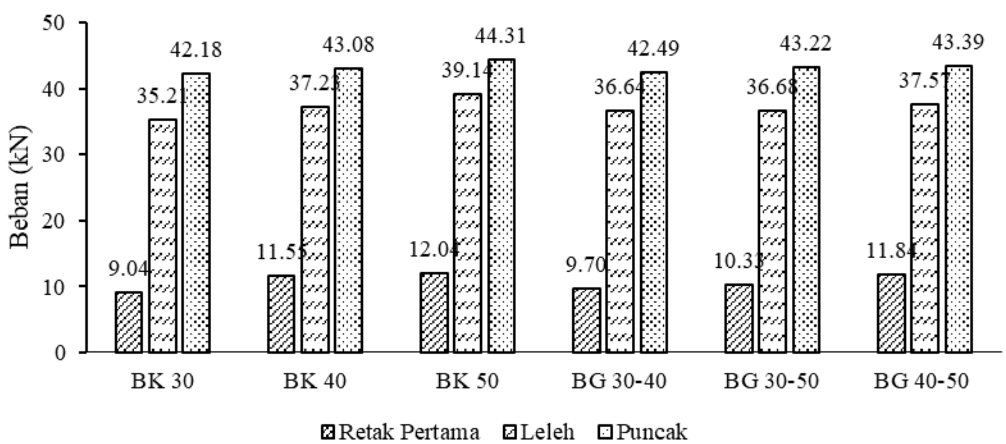

Figure 5. Achievement of Beam Load

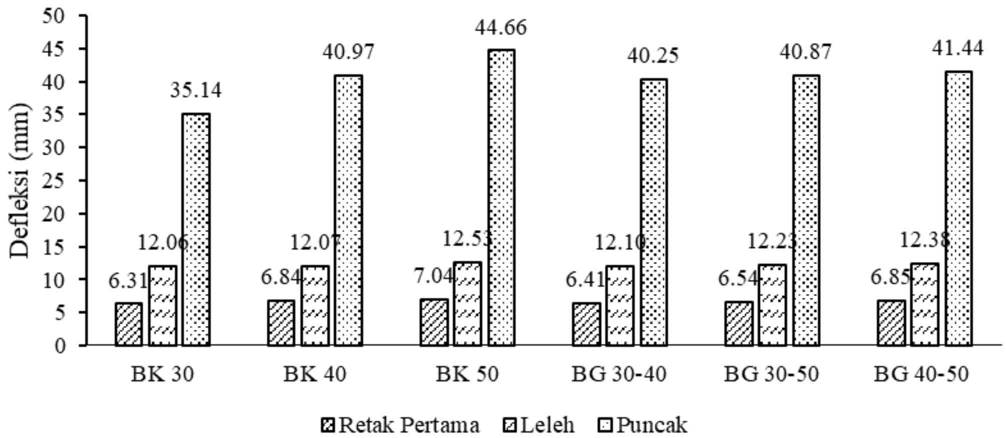

Figure 6. Achievement of Beam Deflection

Beam Load-Deflection

The load borne by the beam causes a compressive response in the top fiber of the beam and a tensile response in the bottom fiber of the beam (Nawy, 1996). The bending stress in the beam causes the beam to deflect. The deflection that continues to increase with increasing load causes cracks in the tensile fiber of the beam. The percentage increase in load performance ranged from 2.47% to 14.27%. The most significant increase in load is found in BG 30-50 against BK 30 which has a difference in quality of compression fiber and tensile fiber of 20 MPa. The disparity in the quality of concrete between the compression fiber and the tensile fiber of the beam is large, which has an impact on the response of the beam resistance in transmitting the load into compressive stresses and tensile stresses in the beam cross section. In beam fibers that are subjected to compressive stress, higher quality concrete has an increasing load resistance characteristic, before the workload is distributed to the lower fibers into tensile stresses (Suhud, 2019).

The deflection of the first crack phase in the beam is reviewed at the same load level. This was done to determine the effect of adding higher quality concrete to the beam on the deflection achieved when the beam has not lost stiffness due to cracking. The most significant deflection reduction pattern occurred in specimens with a difference in concrete quality of 20 MPa, with a percentage of 10.37%. This is due to the higher quality of concrete in the compression fiber of the beam, giving additional rigidity to the entire cross section of the beam. This additional stiffness causes the beam to become stiffer when it deflects compared to a beam with uniform concrete quality or a beam that does not experience an increase in the strength of the concrete in its compression fiber.

The higher quality of concrete can increase the achievement of structural stiffness which is correlated to the reduction of deflection in the beam when viewed at the same load level. Ujianto (2006) stated that the use of high-strength concrete was more significant in increasing the stiffness and strength of the beam compared to using normal-strength concrete. In addition, based on research conducted (Mansor et al., 2020) states that a comparison of displacement ductility between the results of the present study and those of other studies for the normal and lightweight high-strength reinforced concrete beams is detected It can be conclude that the values of μd obtained in this study confirm with those of a similar study by (Leslie et al., 1976; Olivia & Mandal, 2005; Shin et al., 1989), in normal weight high-strength reinforced concrete beams, while they are higher than those reported by (Ahmad & Barker, 1991; Mansor et al., 2019) for lightweight high strength reinforced concrete beams. The results of the comparison of ductility for normal and lightweight high-strength reinforced concrete beams are in accordance with the results of similar studies 14,15,16 in the normal weight of high-strength reinforced concrete beams but these results are in contrast to the results of research conducted 1,17 which states that for beams lightweight high strength reinforced concrete. In structural analysis, stiffness plays an important role in determining the performance of the structure in resisting deformation due to working loads. In beam structural elements that have low stiffness, beams that carry workloads will not play a maximum role in resisting deflection and have low serviceability.

The serviceability of the beam can be measured based on the amount of deflection that the beam can accept (Lüchinger, 1996). SNI 2847-2013 gives the limit of the allowable deflection of the beam L/180, if applied in this study the limit of the allowable deflection of the beam is 8.333 mm. The beam deflection achievement in this study showed that all beam specimens that have been tested have good serviceability and have not reached the allowable deflection limit during the first crack condition. Therefore, beam structural elements that apply the concept of gradation of concrete quality are able to produce a higher level of serviceability than beams that apply uniform concrete quality.

Moment-Curvature of the Beam

Moment-curvature relationship graph is the best solution in evaluating and representing the cross-sectional characteristics of reinforced concrete beams (Dok et al., 2017). The moment-curvature relationship BK and BG is obtained from calculating beam properties using the equations of moment curvature in the trilinear phase proposed by Gang-Kyu et al., (2017). The results of the moment-curvature calculations are summarized in Table 3 and Figure 7.

Table 3. Achievement of Moment-Curvature of Control Beams and Gradient Beams

Benda Uji	Retak Pertama		Leleh		Puncak	
	Momen (kN.mm)	**Kurvatur rad/mm**	**Momen (kN.mm)**	**Kurvatur rad/mm**	**Momen (kN.mm)**	**Kurvatur rad/mm**
BK 30 Teoritis	1.933,41	0,00000138858	9.440,21	0,00001823	9.623,45	0,0000808
BK 40 Teoritis	2.184,22	0,00000138850	9.514,64	0,00001790	9.901,98	0,0000909
BK 50 Teoritis	2.404,79	0,00000138843	9.567,11	0,00001765	10.119,73	0,0000981
BK 30	2.116,26	0,00000138855	8.541,32	0,00001728	8.712,46	0,0000815
BK 40	2.300,92	0,00000138842	8.662,20	0,00001696	9.038,29	0,0000919
BK 50	2.636,49	0,00000138835	8.758,42	0,00001675	9.227,30	0,0000982
BG 30-40 (I)	2.309,14	0,00000138852	8.632,88	0,00001709	8.924,92	0,0000878
BG 30-40 (II)	2.338,37	0,00000138850	8.705,96	0,00001713	8.982,49	0,0000867
Rata-rata	**2.323,75**	**0,00000138851**	**8.669,42**	**0,00001711**	**8.953,71**	**0,0000873**
BG 30-50 (I)	2.508,25	0,00000138844	8.693,01	0,00001697	9.070,17	0,0000918
BG 30-50 (II)	2.413,64	0,00000138843	8.653,78	0,00001697	9.020,80	0,0000914
Rata-rata	**2.460,94**	**0,00000138843**	**8.673,39**	**0,00001697**	**9.045,48**	**0,0000916**
BG 40-50 (I)	2.500,00	0,00000138839	8.728,38	0,00001685	9.185,99	0,0000955
BG 40-50 (II)	2.468,23	0,00000138838	8.713,10	0,00001684	9.176,53	0,0000958
Rata-rata	**2.484,11**	**0,00000138839**	**8.720,74**	**0,00001684**	**9.181,26**	**0,0000956**

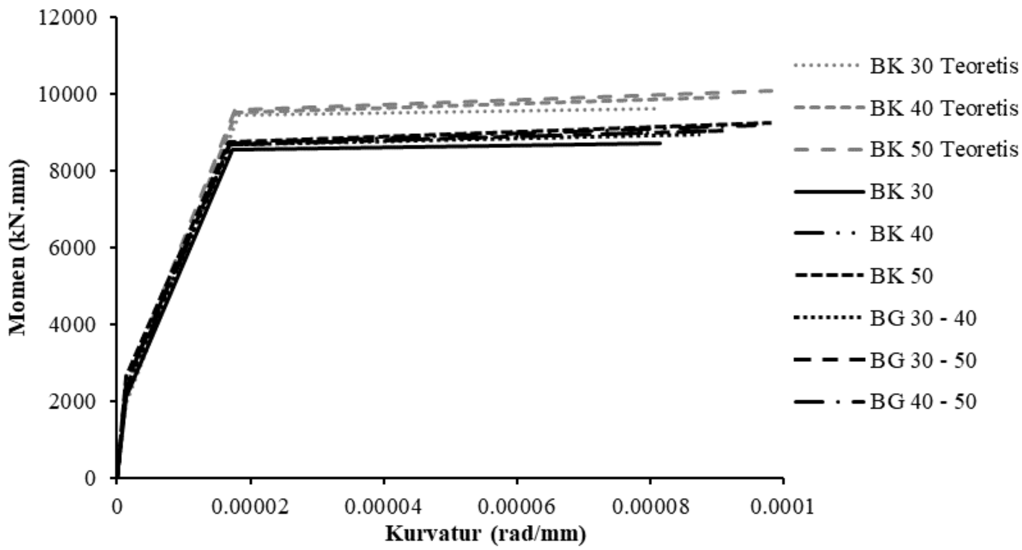

Figure 7. Graph of Theoretical and Experimental Beam-Curve Curve Relationships

The method of analyzing the graph of the moment-curvature relationship is done by comparing the results of the theoretical analysis and the results of the experimental analysis. The purpose of the comparison of the theoretical and experimental moment-curvature relationship is to determine the significance and accuracy of the experimental behavior applied to the beam on the theoretical ideal characteristics of the beam, especially when it comes to the crack phase, yield phase, and peak phase. The comparison of the moment-curvature relationship was only carried out on the BK specimen. This is because the quality of the combined concrete in the BG specimen cannot be calculated and known through a theoretical approach.

In the crack phase, all the specimens compared have different experimental and theoretical moment-curvature curves. The percentage difference between experimental and theoretical reviews ranges from 5.072%-8.788% for moments and 0.002%-0.006% for curvature. This percentage indicates that the theoretical crack moment-curvature calculation analysis is not accurate enough in representing the experimental capacity of the beam when it cracks due to the working load. This is due to the large predicted value of the theoretical effective moment of inertia (Ie) compared to the actual Ie of the beam in the first crack phase.

Higher concrete quality is directly proportional to the increase in the capacity of the crack moment, yield moment, and ultimate moment (MacGregor & Wight, 1997). In experimental beam specimens, increasing the quality of concrete in the compression fiber of the beam by 20 MPa is considered effective and efficient because it only increases the material budget for making concrete blocks by Rp. 7,111.55 or only 0.923% of the budget for making control beams. The higher the increase in the quality of the concrete in the compression fiber, the higher the resistance of the beam to the moment until the first crack appears.

In the melting phase review, the theoretical and experimental yield difference percentage range has a value of 9.233% to 10.524%. The high percentage of the difference in melting moment affects the percentage difference in the experimental yield curvature to the theoretical review of 5.324%-5.504%. The percentage difference in the theoretical yielding moment-curvature to the experimental review is influenced by the difference in the input value of the tensile reinforcement stress (and tensile reinforcement strain) into the yielding moment-curvature calculation equations which have an impact on the difference in the shape of the internal force balance diagram of the beam during yield conditions. (Gang-Kyu et al., 2017). The difference in the values of the two variables is due to the reinforcement properties used in the experimental analysis, which have slightly lower strength and capacity compared to the design or theoretical reinforcement properties. This causes a high difference between the theoretical yielding moment curvature and the experimental moment curvature and tends to be less representative when compared because it has a significance of more than 5%.

The magnitude of the difference in the percentage of moment-curvature in the melting phase affects the overall shape of the experimental moment-curvature curve which is more gentle than the theoretical moment-curvature curve. This is due to the experimentally tested beams starting to lose stiffness due to cracking as the load accumulated on the beams. The slope of the experimental moment-curvature curve is also caused by the influence of the four point bending method which causes the tensile reinforcement to deform along the beam cross section so that the beam tensile reinforcement experiences the actual yield strain slightly earlier than the theoretical yield strain. (Karolina, 2008; Tanuwijaya, 2010).

In the peak-phase moment-curvature review, the percentage range of the theoretical moment difference is 9.152%-10.456% higher than the experimental review. Based on the range of achievement of these percentages, it can be seen that the quality of concrete blocks is theoretically higher than the actual quality of concrete. Paulay & Priestley (1992) states that 85%-95% of the peak moment capacity in the beam structure is influenced by the compressive force of the concrete. Therefore, the strength and peak moment capacity of the beam can be significantly increased by applying high-strength graded concrete in the compression fiber of the beam.

On the other hand, the experimental curvature difference percentage range is 0.113-1.027% higher than the theoretical review. The magnitude of the experimental curvature value compared to the theoretical curvature is due to the fact that in the experimental review, the beam has a lower stiffness due to the accumulation of cracks that cause structural damage to the beam, thus having a greater impact on the curvature response than the theoretical review. (Vertian, 2019).

Deflection Ductility

The resulting beam deflection ductility values ranged from 2.63 to 3.87. The most significant increase of 28.41% occurred in BG 30-50 against BK 30. This significance was due to an increase in the quality of the concrete in the compression fiber of the beam by 20 MPa which was effective in increasing the deflection achievement during the peak phase at a higher loading level. In addition, the peak deflection of the beam is strongly influenced by the presence of compression reinforcement. The application of compression reinforcement does not provide a significant increase in strength of the beam, but can increase ductility, especially in the peak phase. This is due to the combination of the application of higher quality concrete and compressive reinforcement in the beam. Olivia & Mandal (2005) and Nur (2009) reported that the improvement in concrete quality and the magnitude of the ratio ϱ'/ϱ Longitudinal reinforcement can increase the ductility of the beam. Based on SNI 03-1726-2002 Article 4.3.4, reinforced concrete beams with a deflection ductility ratio range of 1.5-5 are included in structural elements with partial ductility characteristics and are very adequate for structural design in earthquake-prone areas. Therefore, the greater the deflection ductility in the grading beam will result in greater structural deformation and a longer time tolerance before the structural element collapses.

Crack Pattern

Cracks formed due to loading need to be limited because they are related to the service level of the structure. As long as the load is applied, the crack patterns that occur are initial cracks and crack propagation, flexural and shear cracks (Krishna et al., 2018; Ashraf et al., 2017). In this experimental study, the flexural loading process of the beam does not stop until the beam is cracked. The flexural loading is continued until the tensile reinforcement is yielded and terminated until the entire specimen exceeds the maximum load. This is done to determine the ductility of the beam deflection whose value is obtained from the yield phase deflection and the peak phase deflection. The crack patterns formed after the flexural testing of the control and gradation beams are presented in Figure 8.

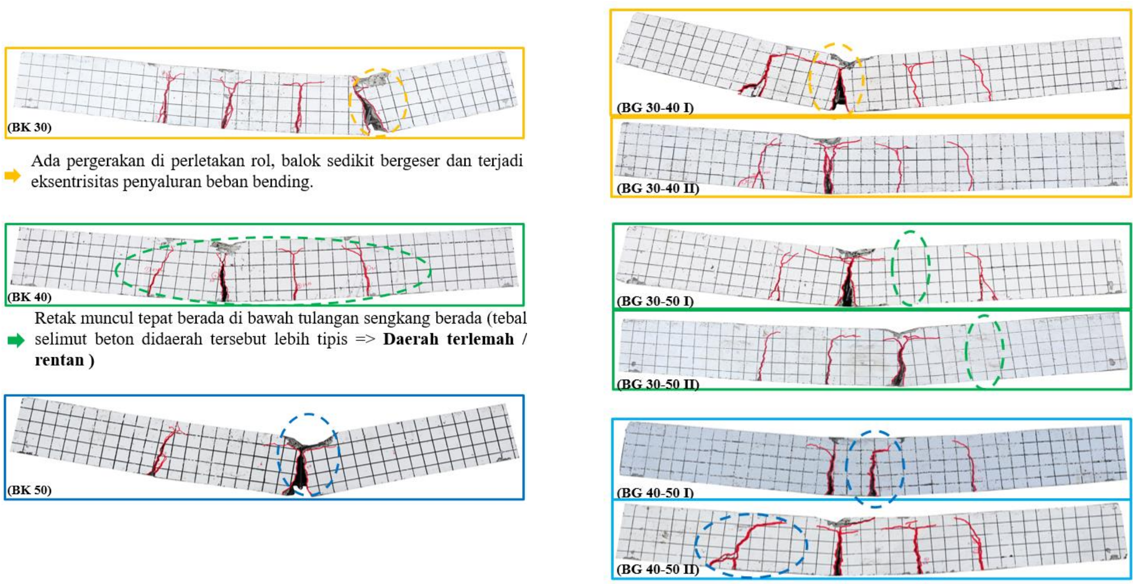

Figure 8. BK and BG Crack Patterns

In this experimental study, reinforced beam specimens were designed with the same shear span ratio (a/d) and beam dimensions. Identical beam design causes the shape and number of crack patterns that occur are not so different between control beams and graded beams (Purnamasari, 2019). The ideal crack pattern is evenly distributed in BK 40. However, in BK 30 and BK 50 there is a large crack anomaly that is concentrated on one side of the beam. This is possible due to external factors in the form of human error and internal factors in the form of uneven distribution of quality in the uneven compaction process which results in the creation of weak areas in the beam, making it susceptible to premature cracking. When the initial setting process of the concrete mix takes place, the trapped air bubbles also harden into air cavities in the concrete. The more cavities in the concrete cause the interaction area of the concrete material with concrete (cohesion bonds) or concrete with reinforcement (adhesion bonds) does not form a perfect bond, so that when the concrete has hardened there is a discontinuity of the stress transfer process on the beam when carrying a workload which is characterized by the appearance of crack concentration (Langi et al., 2018). Strict quality control is required for further experimental studies as this creates data bias in certain specimens.

In the case of the cracked pattern of graded concrete beams, the method of compacting fresh concrete mix by hitting the outside of the formwork using a rubber mallet aims to minimize the risk of mixing the quality of the compression fiber and the tensile fiber quality of the beam, instead causing the creation of air bubbles trapped in the fresh concrete mix. (Purnamasari, 2019). This can be seen concretely in BG 30-40 samples I and II which experienced asymmetric crack concentrations. Another factor that may trigger the concentration of cracks on one side of the beam is that the support reaction cannot provide perfect roller-joint behavior, causing a shift in the IWF loading frame profile. This results in the tilting of the supports, beams, and spreaders which causes the concentration and distribution of workloads to be centered on one leg of the spreader.

BG 30-50 specimens I and II in Figure 8 show a flexural crack pattern consisting of only 3 main cracks. This is due to the configuration method for the quality of the concrete gradation with a difference of 20 MPa on the top fiber and bottom fiber of the beam. The large difference in the quality of the concrete in the graded beam causes discontinuity in the distribution of flexural stresses in the beam. This causes the location of the initial cracks in the beam to be difficult to predict. BG load distribution which has a larger difference in quality will affect the position of the first crack which then spreads to the beam (Suhud, 2019).

In BG 40-50 sample I, flexural cracks only occur at three points. The difference in the configuration of the quality of the concrete in the compression fiber and tensile fiber of the graded beam makes it difficult to choose the right compaction method. Improper compaction methods can reduce the achievement of the compressive strength of concrete or create weakened areas in the concrete structure in local or massive scope. At the implementation stage, the application of compaction control at the boundary layer of graded concrete that should not be mixed is difficult to implement. according to Ardiwinata (2014) The compaction of fresh concrete that is not maximal is the cause of the emergence of a potential anomaly in the crack pattern that is concentrated in the weakest area of the beam due to air voids or material segregation factors.

In BG 40-50 sample II, the first crack appears in the middle of the beam span. After the first crack appears, it is followed by a diagonal crack on the left side of the beam near the pedestal. The support area of the beam is dominated by internal forces in the form of shear forces. Structural failure due to shear forces forms a diagonal crack pattern. Amri (2005) states that if the flexural ability of reinforced concrete beams is exceeded, the damage will continue with the formation of shear cracks. However, in BG 40-50 sample II the shear crack pattern has been formed since the first crack propagation until before the maximum flexural loading is reached. This is most likely due to the weakening in the area, namely the tilt of the stirrup reinforcement which is in charge of resisting shearing. The tilted position of the shear reinforcement results in the absence of reinforcement that can withstand the load on the beam, resulting in a crack pattern due to shear failure (Arifanda, 2019).

Conclusion

The shape of the load-deflection relationship curve for graded concrete beams that experienced an increase in quality at the compression fiber was steeper than the load-deflection relationship curve for the control beam. The most significant results were found in BG 30-50 against BK 30 which had an increase in load-bearing capacity of 14.27% and a reduction in deflection of 10.34% in the crack phase. This indicates that the increase in the quality of the concrete in the compression fiber of the graded beam contributes to an increase in capacity, stiffness, and serviceability in the post-crack phase.

The theoretical moment-curvature relationship graph model before the melting phase is steeper than the experimental moment-curvature relationship graph and is steeper when the post-melting phase is exceeded. This is caused by the experimental treatment and implementation method applied to the beam, affecting the capacity and property of the material making up the beam lower than its theoretical property. Increasing the quality of concrete in compression fiber by 20 MPa is considered effective and has a positive impact on the moment-curvature capacity of the beam because it only increases the use of material costs by Rp. 7,111.55 or only 0.923% of the budget for making control beams. The deflection ductility produced by the beams in this study ranged from 1.5-5, including structural elements with partial ductility characteristics and very adequate for structural design in earthquake-prone areas.

The shape of the crack pattern that appears on BK and BG is in the form of flexural cracks. The large concentration of cracks in the BK 30 and BK 50 specimens was caused by material quality factors and the presence of imperfect concrete compaction factors causing air voids. Anomalies of cracks occur in specimens 30-50 which have a quality difference of 20 MPa in the tensile and compressive fibers causing the location of the appearance of the crack pattern to be difficult to predict. Shear cracks occurred in specimen BG 40-50 sample II indicating shear failure due to the technical installation of slanted stirrup reinforcement.

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