PARAMETRIC STUDY OF REINFORCED CONCRETE BEAM SUBJECTED TO IMPACT LOADING USING FINITE ELEMENT ANALYSIS

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ABSTRACT

Impact loading design is crucial in specific structures, but there are no simpler method to design reinforced concrete members to impact loads other than performing extensive experimental works, studies and simulations, as the dynamic behavior of reinforced concrete member is harder to predict unlike reinforced concrete structural member under static load, which is commonly designed under the Ultimate Limit State. Therefore, this research aims to perform a parametric study on the dynamic behavior of the beams under impact loading.

Parameters including longitudinal reinforcement steel ratio, shear reinforcement steel ratio and aspect ratio is checked against the drop weight under Impact Loading Test, where the mid-span of the beam will be subjected to the applied load of a free-falling drop weight with a certain mass and velocity. The accuracy of the beam model for this project is validated to Fujikake et al.'s [8] experimental results on the impact responses of reinforced concrete beams by performing Finite Element Analysis using the software LS-DYNA. The exact same model is then used for the parametric study with varying parameters of interest as stated above.

Among the outcomes of this project include the maximum deflection at the mid span of the beam model, the maximum impact forces at failure experienced by the beam and the maximum reaction forces at the bottom supports of the simply support beam models. The purpose of this project is to have a better understanding on the impact responses of reinforced concrete beam, where the generated results may be used to validate or modify empirical formulas produced by other researches, or even create new ones regarding prediction of dynamic behavior of reinforced concrete beams.

1 Introduction

While the current popular design of structure according to ultimate limit state concept suffices to an extent to keep the structure safe, some reinforced concrete structures have to be designed more accurately for impact loads such as structures with high exposure to rockfalls or factories dealing with falling heavy loads [4]. This is to ensure a more precise evaluation of the structure against impact loads and to predict the failure probability.

Most researches on impact loading are done in order to enhance the general knowledge on the dynamic behavior of reinforced concrete members, as it is far more unpredictable and vastly different from the static behavior. Other researches are also done in an attempt to come up with simplified calculation methods to predict the dynamic response of reinforced concrete structures [2] [4] [5]. These are admirable initiatives, as the dynamic behaviors of reinforced concrete is currently heavily dependent on performing numerous simulations and experimental works. However, as far as the author comprehends, there are still insufficient evidences on the results obtained to confirm their reliability.

The purpose of this study is to perform a parametric study on the dynamic behavior of reinforced concrete beam when subjected to impact load at its mid-span. For the parametric study of the structural behavior of the beam, the parameters that will be monitored include the tensile reinforcement ratio, shear reinforcement ratio and the shear span to depth (a/d) ratio in relation to the drop weight mass and velocity at contact.

2 Literature Review

Fujikake et al. [8], Jiang et al. [9] and Adhikary et al. [5] carried out impact load test, where the ultimate load carrying capacity, stiffness and energy absorption of RC beams were monitored. The results from all the aforementioned papers indicated that under static and low loading rates, the RC beam undergoes a flexural failure as the stress are distributed almost uniformly from the impact point to the tension side of the support. However, under high loading rates, the beams under impact load exhibited localized failure, and the flexural cracks do not reach the supports at both sides. Therefore, it shows that high loading rates significantly influence the behavior of reinforced concrete structural elements with increase in resistance and change in failure mode of the structural members.

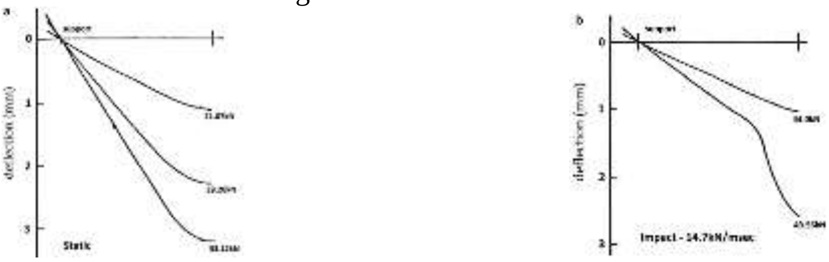

Figure 1. Deflected shapes predicted for RC beams under static loading and impact loading [1].

In general, it has been accepted that the aspect ratio of 2 - 2.5 is the critical ratio for static loading [11] [20], where values with aspect ratio lower than this will result in shear failure on beams whereas beams higher aspect ratios exhibit flexural failure. This phenomenon is tested by Perdomo et al. [10], and the study has shown that for beams and columns of large aspect ratios, the most important effect is bending or deflection. But with its reduction, shear stresses become progressively more dominant. This finding was supported by Sharma and Ozbolt [11], who carried out a numerical study on a rectangular RC cantilever beam with a varying aspect ratio of 2, 4, 6 and 8, all subjected to low to high drift rates. It was found that, at the highest drift rate, for beam with aspect ratio of 2, shear failure is observed along with shear-compression cracks. As the aspect ratio increases, flexure-shear cracks accompanied by cover peeling leads to the failure of the beams. These findings are only applicable for beams with longitudinal reinforcement ratio of 0.5% and above, as the failure mode of the beam is mainly flexural at low longitudinal reinforcement ratios regardless of the a/d ratio [20]. In relation to aspect ratio and the resistivity of reinforced concrete beams under varying loading rates, it is [11] also found out that at an increase in loading rate, the tensile stresses experienced in the beam does not reach the support, in fact it is getting nearer to the applied load.

Apart from testing on the influences of aspect ratio on the dynamic behavior of beam, Ozbolt and Sharma [12] also performed a numerical simulation of RC beams with different shear reinforcements. Based on their numerical results obtained, they have reached a conclusion that the static reaction depends largely on the amount of shear reinforcement and whether the beams are designed to be shear or flexural critical whereas the dynamic reactions of the beams were found to be independent of the amount of shear reinforcement as well as whether the beam is flexural critical or shear critical. As long as there are sufficient shear reinforcements, well distributed cracks tend to form in the beams. This conclusion is agreeable with Saatci and Vecchio's [22] findings. However, they added that even though the shear reinforcement does not affect the failure mode much, it is observed that specimens with higher shear capacity has higher impact resistance force and is able to absorb more energy, similar to the findings of varying longitudinal reinforcement ratio.

For simulation, since this LS-DYNA provides a vast number of material models, it is crucial to choose the most suitable ones in order to simulate the models as according to the actual experimental work accurately. For the study, the concrete beam is modelled using the material Concrete Damage Rel. 3 or MAT_072R3, also known as the K&C Concrete Model. The default parameter of this model has been calibrated using a well characterized concrete with available uniaxial, biaxial, and triaxial test data in both tension and compression [16]. The input for this material keyword includes mass density of concrete, Poisson's ratio, unconfined compression strength and the defined effective strain-rate effects curve. The effective strain rate curve used in this study is extracted from Malvar's study [18] [21], where the dynamic increase factor (DIF) needed for high strain rate cases in terms of strain factor against time is considered.

The material properties of reinforcement steel bars for both longitudinal and also shear are inputted into the software through the keyword MAT_003-Plastic Kinematic. This model is suited to model isotropic and kinematic hardening plasticity with the option of including rate effects [13]. Among the inputs for this keyword are the mass density, Young's modulus, Poisson's ratio and yield strength of steel. The dynamic effects of strain rates are taken into account by scaling yield stress with the Cowper-Symonds model factor.

3 Methodology

The parametric study of the behavior of the beam under impact loading is to be carried out using Finite Element Method by using the software LS-DYNA. However, before commencing the beam modeling for the intended objective of this paper, the validation of the modeling of the beam on LS-DYNA with actual experimental results done by Fujikake et al. [8] has been made to ensure that the beam model is functional and the simulation inputs are correct. After matching the simulation material responses to the experimental results, an element mesh size sensitivity check is done to ensure that the mesh size chosen for the beam, tensile and shear reinforcements' would give the most accurate material and structural responses.

The parametric study of reinforced concrete beam was done after completing the above validation and sensitivity check. For the parametric study, the cross section of the beam model is set to be a fixed dimension of 150mm width x 250mm depth, with two longitudinal reinforcement steel bars of diameters 16mm, 20mm, 22mm and 25mm (all with the same yield strength of 500MPa) at both tension and compression side. One part of the beam specimens are tested without any shear reinforcement, whereas another part of the beam specimens are shear-reinforced with steel bars of 6mm diameter and yield strength of 295 MPa, with a varying percentage of 0.1%, 0.2%, 0.3% and 0.4%. The cover of the link to the outer surface of beam is set to be a fixed 50mm for all specimens. The length of beam specimens vary depending on the a/d ratio, of which the values 2, 3, 4 and 5 is be tested. Concrete strength is set to be 30 MPa, with Poisson's ratio value of 0.02.

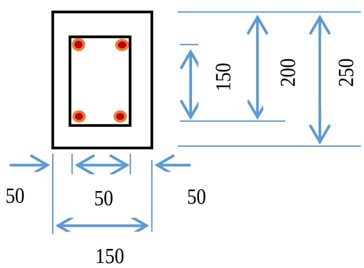

Figure 2. Details of the arrangement of reinforcement bars: Cross-sectional view, unit = mm.

All the specimens are tested with the same velocity and same mass of drop weight, which are 6 m/s and 400 kg respectively. The aforementioned specifications of the beams are combined and done in different series, where each beam models have either different a/d ratio, main reinforcement percentage or shear reinforcement ratio (project activity as listed in chapter 3.4). There are a total of 60 beam models to be analyzed.

The beam is modeled out in LS-DYNA using a mesh of 25mm. For the beam model's material properties, both reinforcement bars and the stirrups have the inputs as *Mat 003 Plastic Kinematic*, where all the data are taken to be as the properties of mild steel (Modulus of Elasticity = 210 GPa, mass density = 7850 kg/m3). This material model is used to apply both the initial elastic data as well as the secondary plastic (post yield) portion of the stress-strain curve. The concrete body is subjected to Mat 072R3-Concrete_Damage_REL3. Duplicated nodes between the reinforcement bars, stirrups and the concrete are merged in order to signify a perfect bonding between all the materials. All these inputs are the same as the validation model.

4 Results

Tensile Reinforcement Ratio

Without Shear-Reinforcement

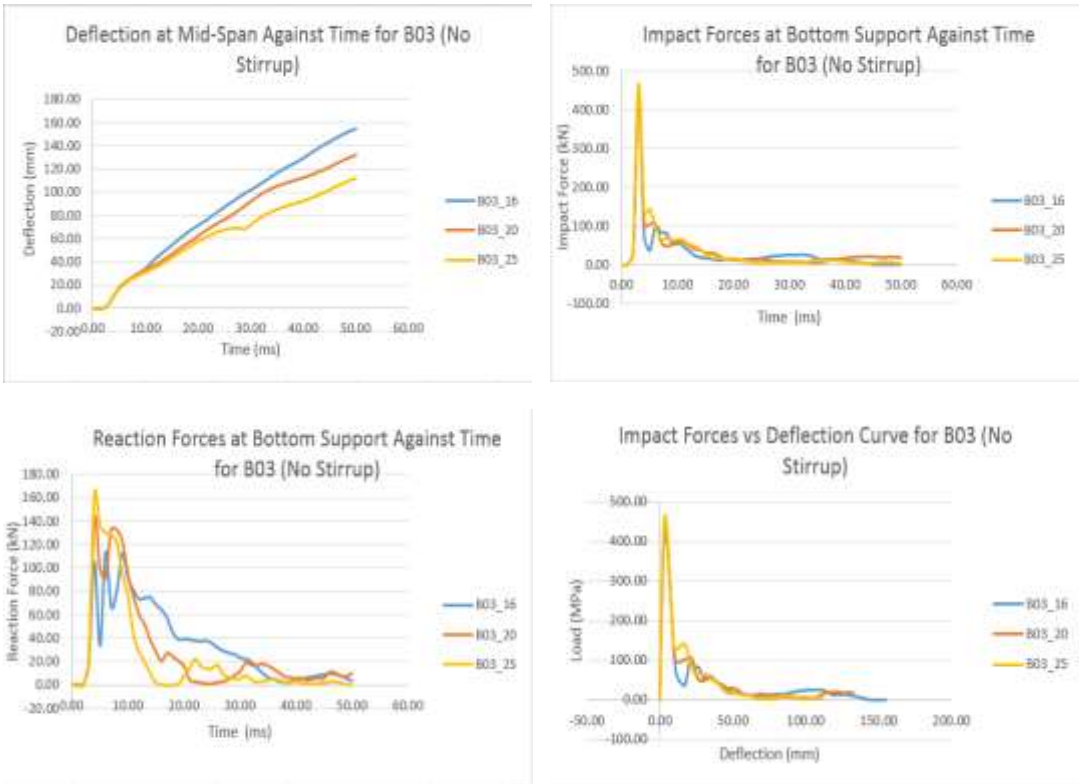

Figure 3. Graphs of the impact responses exhibited with respect to longitudinal reinforcement ratio by the beam models with a/d ratio = 3 and without shear reinforcement

Table 1. Tabulated impact responses exhibited with respect to longitudinal reinforcement ratio by the beam models with a/d ratio = 3 and without shear reinforcement

Rebar Size (mm)	Max. Deflection(mm)	Max. Reaction Force (kN)	Max. Impact Force (kN)
16	154.71	113.38	432.82
20	132.62	142.29	446.38
25	112.02	163.81	465.73

With Shear-Reinforcement (Ratio = 0.3%)

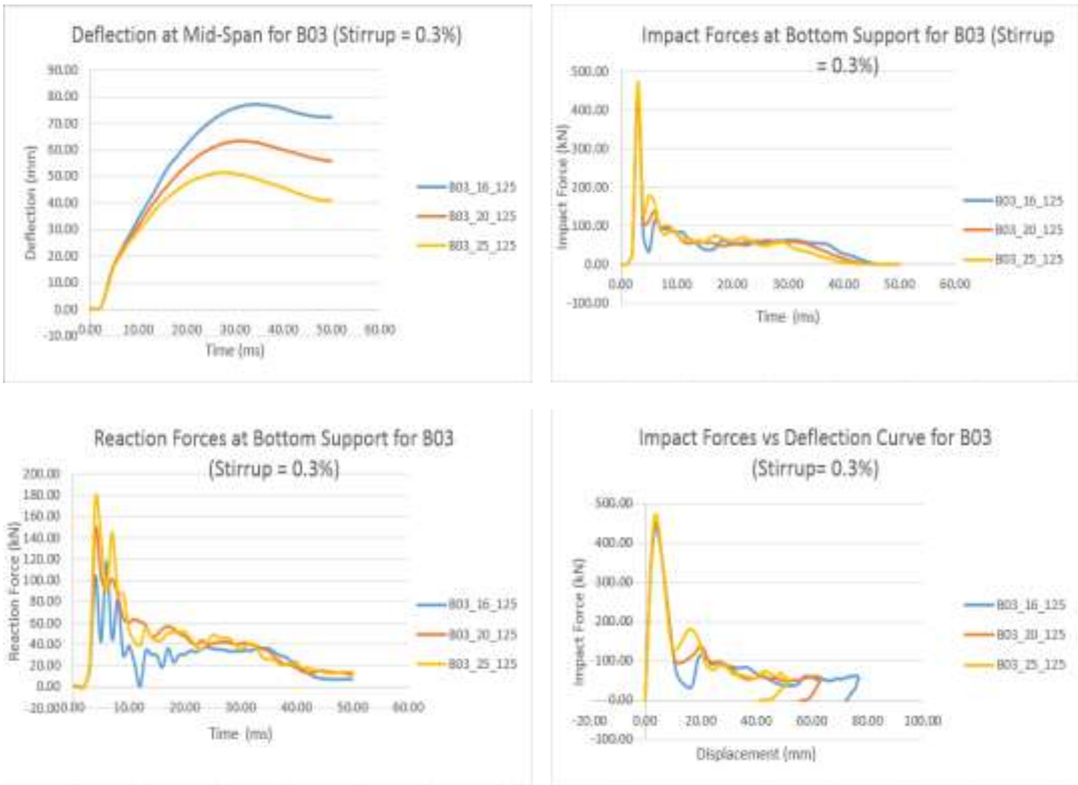

Figure 4. Graphs of the impact responses exhibited with respect to longitudinal reinforcement ratio by the beam models with a/d ratio = 3 and with shear reinforcement ratio of 0.3%

Table 2. Tabulated impact responses exhibited with respect to longitudinal reinforcement ratio by the beam models with a/d ratio = 3 and with shear reinforcement ratio of 0.3%

Rebar Size (mm)	Max. Deflection (kN)	Max. Reaction Force (kN)	Max. Impact Force (kN)
16	76.98	117.51	438.08
20	63.53	148.41	453.02
25	51.51	176.08	472.90

In terms of impact forces at point of contact between drop weight and the surface of beam model, the beams were found to fail at higher loads with the increase in the longitudinal reinforcement ratio, signifying that there is an increase in load carrying capacity in the beam. This reaction is in lieu with what Banthia and Mindesss and et. al mentioned [7] [1] [2] [8], that concrete beams show higher impact strength and higher fracture energies at higher stressing rates.

As for the maximum vertical displacement, it was as predicted to decrease when the longitudinal reinforcement ratio increase. However, the more interesting part of finding is that, even though the mass of drop weight and drop velocity remains the same, the reaction forces at the bottom supports increases as the rebar size increases, which is different from the behavior of beams applied with static load, where the sum of reaction forces should equal the load applied to the structural member.

Shear Reinforcement Ratio

a/d ratio = 3

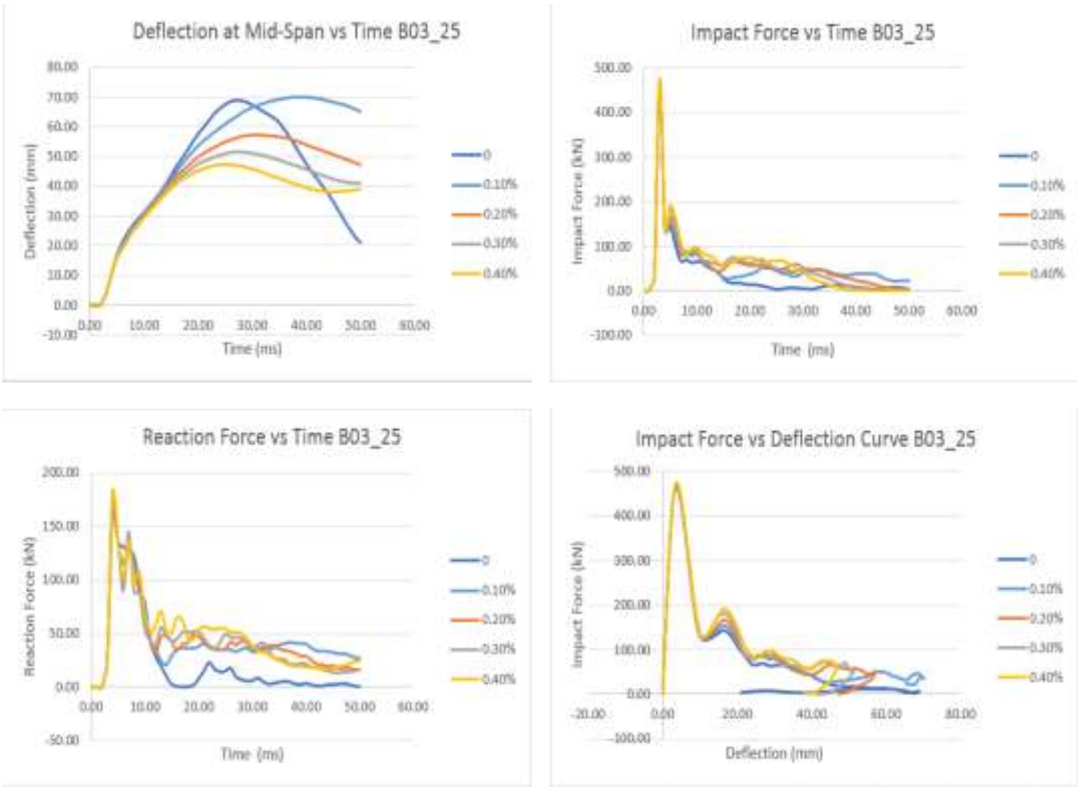

Figure 5. Graphs of the impact responses with respect to shear reinforcement ratio exhibited by the beam models with a/d ratio = 3 and with main reinforcements of 2T25.

Table 3. Tabulated impact responses with respect to shear reinforcement ratio exhibited by the beam models with a/d ratio = 3 and with main reinforcements of 2T25.

Stirrup Ratio (%)	**Max. Deflection(mm)**	**Max. Reaction Force (kN)**	**Max. Reaction Force (kN)**
0	68.99	163.81	465.73
0.1	70.16	169.20	471.92
0.2	57.23	174.33	472.71
0.3	51.51	176.08	472.90
0.4	47.26	180.51	474.99

For the parameter of varying shear reinforcement ratio, beam models with higher shear reinforcements have higher impact resistance force, similar to the behavior of increasing tensile reinforcement ratios and agreeing with Saatci and Vecchio [22], but the increase in the impact resistance force is not that significant.

As for the maximum deflection, with the increase of shear reinforcement ratio, there is a decrease in the maximum deflection value. However, for graphs with shear reinforcement ratio = 0, it can be seen that there is a sharp drop after the beam reaches its maximum deflection. This is due to the limitation of the material card that is used to model out the concrete damage, which is *MAT 072*. When the material reaches a state where it totally fails, instead of performing element deletions, the material card will enable the model to go into a softening response, of which the model becomes unstable.

In terms of reaction forces, it can be observed that with an increase in shear reinforcement ratio, there is an increase in maximum reaction forces at the bottom supports, meaning that the additional stirrups can actually help in the transfer of impact forces experienced by the beam model to the bottom supports.

Shear Span-to-Effective Depth Ratio (a/d)

Without Shear Reinforcement

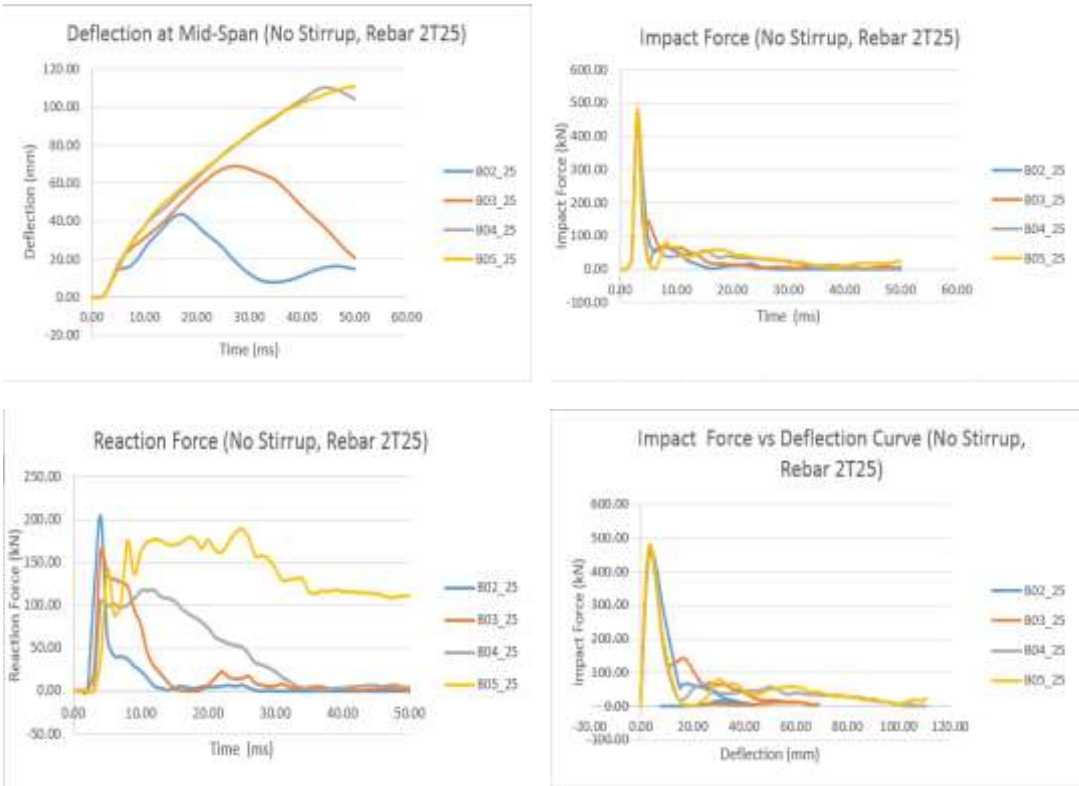

Figure 6. Graphs of the impact responses with respect to a/d ratio exhibited by the beam models without shear reinforcements and with main reinforcements of 2T25.

Table 4. Tabulated impact responses in respect to a/d ratio exhibited by the beam models without shear reinforcements and with main reinforcements of 2T25.

a/d ratio	Max Deflection (mm)	Max. Reaction Force (kN)	Max. Impact Force (kN)
2	43.74	203.75	460.88
3	68.99	163.81	465.73
4	110.39	116.88	477.30
5	110.80	189.08	481.50

With Shear-Reinforcement Ratio = 0.2%

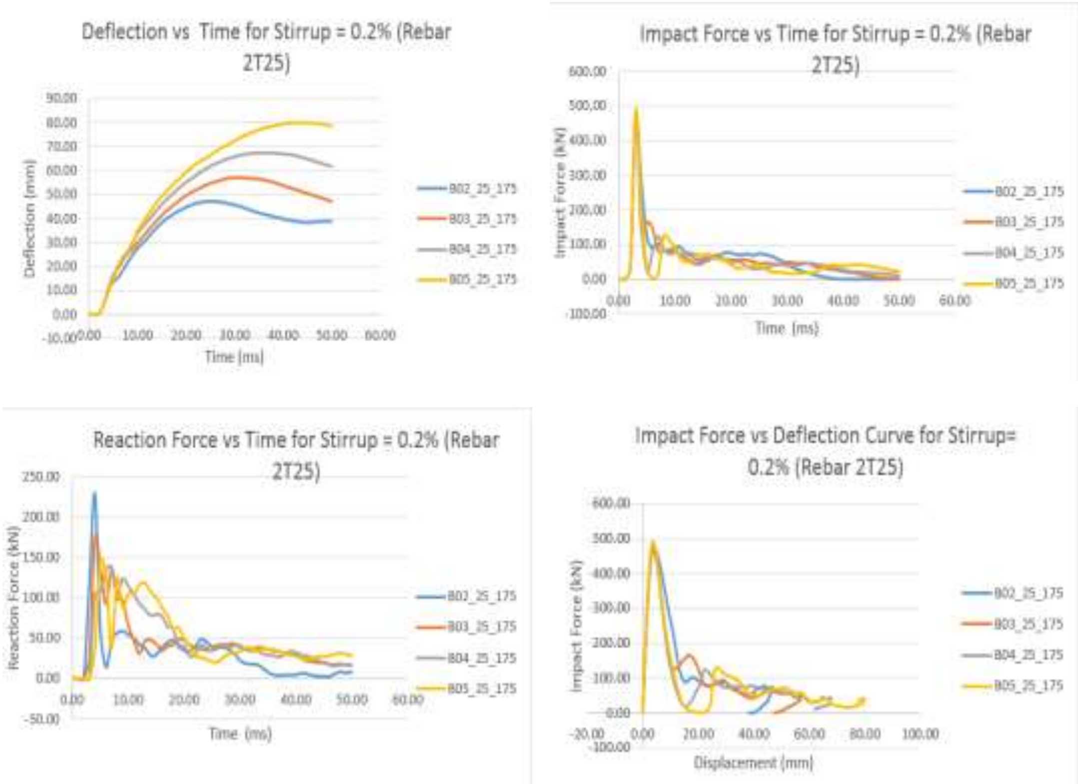

Figure 7. Graphs of the impact responses with respect to a/d ratio exhibited by the beam models with shear reinforcement of ratio = 0.2% and with main reinforcements of 2T25.

Table 5. Tabulated impact responses in respect to a/d ratio exhibited by the beam models with shear reinforcement of ratio = 0.2% and with main reinforcements of 2T25.

a/d ratio	Max Deflection (mm)	Max. Reaction Force (kN)	Max. Impact Force (kN)
2	46.93	229.38	467.07
3	57.23	174.33	472.71
4	67.53	138.58	484.21
5	80.08	146.00	488.23

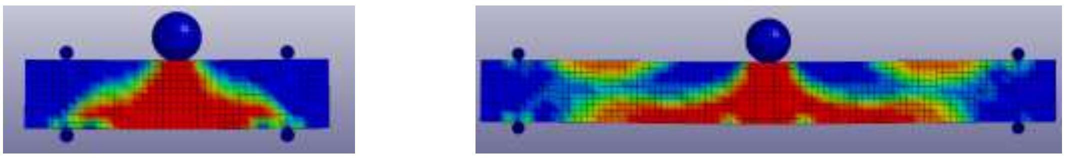

Figure 8. Plot of effective strain distribution in LS-DYNA for beam models with a/d ratio = 2 and 5 respectively.

In terms of aspect ratio, it appears that with an increase in a/d ratio, the tensile stresses experienced in the beam does not reach the support. The area of tensile stresses has increased relatively, but the distance between the end of tensile stresses when it reaches the bottom surface of beam and the bottom support are getting further apart. This phenomenon was also observed by Sharma and Ozbolt [11], whom deduced that it is due to initial forces caused by the high loading rate.

Besides, in static behavior, usually beams with low a/d ratio especially with ratio of 2 and lower will fail in shear, and the ones with higher ratio tend to fail in flexure. However, as observed from the figure above, the beam with a/d ratio of 2 seems to potentially fail in flexure, whereas the one with a/d ratio of 5 apparently has the potential to fail in either flexure or shear-compression mode. However, this visual observation might not be able to depict the actual failure mode of the beam. This is because even though *MAT 072* is good in describing the material responses, but it does not seem to be able to reproduce structural responses, but requires additional material cards such as *Mat Add Erosion.*

In the graphs of reaction forces against time, it is apparent that for beams without shear reinforcements, there is not much difference in terms of reaction forces at the bottom supports in cases with different a/d ratio, but as shear reinforcements are added in, there is s a major increase in the reaction forces at the bottom supports with the increase of a/d ratio.

5 Conclusion and Recommendations

In conclusion, a parametric study has been done for reinforcement concrete beams subjected to impact loading via simulation by using the non-linear finite element analysis software LS-DYNA. The parameters tested including variation of longitudinal reinforcement ratio, shear reinforcement ratio and aspect (a/d) ratio. The simulation was done by performing a Falling Weight Impact Loading Test, where a drop weight of 400 kg is to fell without any constraints (free fall) unto the mid-span of a simply-supported beam, of which has a cross-section of 150mm width to 250 mm depth.

From the results, it can be concluded that:

1) With an increase in longitudinal reinforcement ratio and shear reinforcement ratio, there is an increase in impact resistance forces of the beam models, meaning that the beams have a higher load-carrying capacity.
2) The variation of a/d ratio does not seem to have much effect on the maximum impact forces.
3) The increase in longitudinal reinforcement ratio and shear reinforcement ratio has predictably decreased the maximum deflection experienced by the beam model, which increases as the a/d ratio of the beam model increases.
4) The reaction forces at the bottom supports of the beam models seemingly increases with the increase of longitudinal reinforcement ratio and shear reinforcement ratio, even when the mass of drop weight and the drop velocity is fixed throughout the whole experiment.
5) In the case of increasing a/d ratio, the reaction forces experienced at the bottom supports decreases, as the tensile stresses experienced by the beam does not reach the support due to inertial forces.

The failure mode of beams with varying a/d ratio for dynamic cases is an interesting aspect to check on, but due to the limitations of the material card used to simulate the concrete damage of the model, author was not able to confirm the beam models' failure modes.

The dynamic behavior of reinforced concrete beam is vastly different from the ones subjected to static loading. By performing this parametric study, the structural engineering community can hopefully have a better understanding on the way reinforced concrete beams behave when subjected to impact loading. Plus, there are so many potentials that can be done using the findings of the research, especially to validate the empirical formulas generated by the other researchers to predict the dynamic behavior of reinforced concrete members, to modify them or even come up with a new one based on these findings. This can be very beneficial, not only to the structural engineering community, but also the public by making a structure safer.

6 References

[1] A. Miyamoto, M. E. King, and M. Fujii, "Non-linear Dynamic Analysis and Design Concepts for RC Beams Under Impulsive Loads," *New Zealand Nat. Soc. Earthquake Eng. Bull.*, pp. 98-111, 1989.

[2] D. M. Cotsovos, "A simplified approach for assessing the load-carrying capacity of reinforced concrete beams under concentrated load applied at high rates," *International Journal of Impact Engineering*, vol. 37, pp. 907-917, 8// 2010.

[3] B. Mosley, J. Bungey, and R. Hulse, *Reinforced Concrete Design to Eurocode 2*, 7 ed. UK: Palgrave Macmillan, 2012.
[4] N. Kishi and H. Mikami, "Empirical Formulas for Designing Reinforced Concrete Beams under Impact Loading," *Structural Journal*, vol. 109, 7/1/2012 2012.
[5] S. D. Adhikary, B. Li, and K. Fujikake, "Dynamic behavior of reinforced concrete beams under varying rates of concentrated loading," *International Journal of Impact Engineering*, vol. 47, pp. 24-38, 9// 2012.
[6] N. Kishi and A. Q. Bhatti, "An equivalent fracture energy concept for nonlinear dynamic response analysis of prototype RC girders subjected to falling-weight impact loading," *International Journal of Impact Engineering*, vol. 37, pp. 103-113, 1// 2010.
[7] N. P. Banthia, S. Mindess, and A. Bentur, "Impact behaviour of concrete beams," *Materials and Structures*, vol. 20, pp. 293-302, 1987/07/01 1987.
[8] K. Fujikake, B. Li, and S. Soeun, "Impact Response of Reinforced Concrete Beam and Its Analytical Evaluation," *Journal of Structural Engineering*, vol. 135, pp. 938-950, 2009/08/01 2009.
[9] H. Jiang, X. Wang, and S. He, "Numerical simulation of impact tests on reinforced concrete beams," *Materials & Design*, vol. 39, pp. 111-120, 8// 2012.
[10] M. E. Perdomo, R. Picón, M. E. Marante, F. Hild, S. Roux, and J. Flórez-López, "Experimental analysis and mathematical modeling of fracture in RC elements with any aspect ratio," *Engineering Structures*, vol. 46, pp. 407-416, 1// 2013.
[11] A. Sharma and J. Ožbolt, "Influence of high loading rates on behavior of reinforced concrete beams with different aspect ratios – A numerical study," *Engineering Structures*, vol. 79, pp. 297-308, 11/15/ 2014.
[12] J. Ožbolt and A. Sharma, "Numerical simulation of reinforced concrete beams with different shear reinforcements under dynamic impact loads," *International Journal of Impact Engineering*, vol. 38, pp. 940-950, 12// 2011.
[13] L. S. T. Corporation, "LS-Dyna Keyword User's Manual," *Material Models*, vol. II, 2014.
[14] D. M. Cotsovos and M. N. Pavlović, "Modelling of RC beams under impact loading," *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, vol. 165, pp. 77-94, 2012.
[15] V. Gyliene and V. Ostasevicius, "Cowper-Symonds material deformation law application in material cutting process using LS-DYNA FE code: turning and milling," in *8th European LS-DYNA Users' Conference*.
[16] M. C. Jaime, "Numerical modeling of rock cutting and its associated fragmentation process using the Finite Element Method," 2012.
[17] M. A. K. M. Madurapperuma and A. C. Wijeyewickrema, "Columns in Reinforced Concrete Buildings Impacted by Tsunami Water-Borne Massive Objects," 2012.
[18] L. J. Malvar and C. A. Ross, "Review of Strain Rate Effects for Concrete in Tension," *Materials Journal*, vol. 95, 11/1/1998 1998.
[19] J. K. Paik and A. K. Thayamballi, *Ultimate Limit State Design of Steel-Plated Structures*: John Wiley & Sons, 2003.
[20] G. S. H. Samir A. Ashour and F. W. Faisal, "Shear Behavior of High-Strength Fiber Reinforced Concrete Beams," *Structural Journal*, vol. 89, 3/1/1992 1992.
[21] L. E. Schwer and L. J. Malvar, "Simplified concrete modeling with *Mat_Concrete_Damage_Rel3," 2005.
[22] S. Saatci and J. F. Vecchio, "Effects of Shear Mechanisms on Impact Behavior of Reinforced Concrete Beams," *Structural Journal*, vol. 106, 1/1/2009 2009.
[23] G. Thiagarajan, A. V. Kadambi, S. Robert, and C. F. Johnson, "Experimental and finite element analysis of doubly reinforced concrete slabs subjected to blast loads," *International Journal of Impact Engineering*, vol. 75, pp. 162-173, 1// 2015.