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Structural Reliability of Dapped End Beams with Different Reinforcement Layouts under Dynamic Loading

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Abstract. Reinforced concrete Dapped End Beams (DEB), also known as half-joints, are used in bridges and many other pre-cast constructions to reduce end depth and increase lateral stability. Dapped end beams are expected to experience dynamic loads when used in bridges, the available past studies on the behavior and damage assessment of DEBs are mainly for static loading. The reinforcement layouts of DEBs can influence the behavior of these shear critical members under impact loading. Better understanding of the crack propagation and failure patter of DEBs under dynamics loads is required for safe and economic design of these structural elements. A non-linear numerical transient study was conducted to investigate the dynamic performance of DEBs with different reinforcement layouts. Advanced material models capable of including strain-rate effect and material non-linearity to capture realistic behavior of DEBs were used. The simulated models in finite element package LS-DYNA were verified and used to conduct detailed parametric study to investigate the impact behavior of DEBs with different reinforcement layouts. Sensitivity of concrete compressive strength, main dapped end reinforcement and special shear reinforcement detailing on the structural reliability of DEBs were studied.

1. Introduction

Dapped end beams are considered as shear critical structural elements due to the unusual shape at the beam ends where special design consideration is required due to sever stress flow disturbance [1]. Many studies have been completed on the behavior of DEBs when subjected to static loads [2-5]. In those studies, the main parameters observed were concrete strength, reinforcement layouts and cross-sectional dimensions of the beams. Under the applied static load, diagonal cracks will develop at the re-entrant corner, and as load increases, diagonal cracks will propagate towards the point of loading [4]. Cross-sectional dimensions played an important role in controlling the diagonal cracks [4]. Similarly, Aswin *et al.* [5] showed that higher dapped-end height provides higher failure load capacity. Moreover, concrete strength also has an effect on the shear strength of DEBs was shown in a study completed by Lu *et al.* [2], where the performance of dapped-end beams using high strength concrete showed that shear strength of DEBs increases with the increase of concrete compressive strength. The effect of reinforcement of dapped-end beam on its capacity and performance under static load has been also observed. Increasing the reinforcement ratio will enhance the strength capacity of these beams [5]. Minimizing the spacing between stirrups and increasing number of stirrups enhance the strength capacity of dapped-end beams under static load [3,4]. Similarly, inclined stirrups and bent reinforcement also were proven to increase the load capacity of dapped end beams when subjected to static loads [3, 4]. A recent study observed the effect of reinforcement layouts on the static behavior of DEBs [6]. Variation between diagonal, shear and horizontal reinforcement was done in the four beams in order to observe their effect on the load carrying capacity of dapped end beams under static loads. The study showed that under static load, the greatest impact on the failure load was seen in the beam without diagonal reinforcing bars. Beams with no diagonal or bent bars experienced failure in the nib area. Findings of this study [6] showed that reinforcement layouts have significant impact on the strength capacity of dapped-end beams.

Although, dapped-end beams are often exposed to dynamic loading, the dynamic behavior of dapped-end beams is not well established yet. In recent years, a growing interest has been observed in the field of structural behavior and response under dynamic loading which may involve large displacements, material non-linearity, elastic and plastic instability and material behavior under high strain rates. This research presents a study on dapped end beams for different layouts of main and hanger reinforcements for different concrete grades. Main parameters included in the study are concrete compressive strength, detailing of main dapped end reinforcement and special shear reinforcement (hanger reinforcement).

2. Finite Element Modeling

The finite element analysis software LS-DYNA was used in was used in performing the structural response predictions. Many studies have been completed on the behavior of rectangular beams under dynamic loading [7-10]. Verification of the modeling techniques and selected material models was done by modeling a previously tested rectangular beam by Zhan *et al.* [7]. All the modeling approaches and material models were verified by comparing simulation results with experimental results for rectangular beams. Once verified, same modeling techniques and approaches were followed in simulating DEBs. Due considerations were taken in element modeling, contact algorithms, material modeling, boundary conditions and load application. Detailed finite element modeling procedure is presented in a separate study [11]. All the properties related to the previously experimented beam were taken from Lu *et al.* [2]. The overall dimensions and reinforcement layout of the selected beam are shown in Figures 1 and 2.

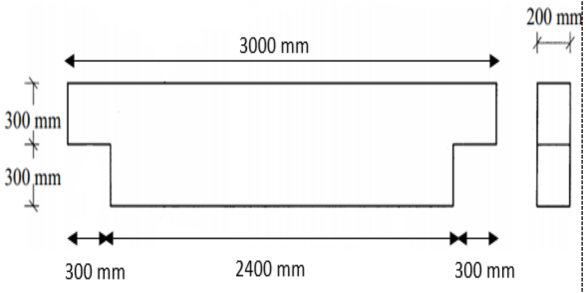


Figure 1. Dapped end beam configuration.

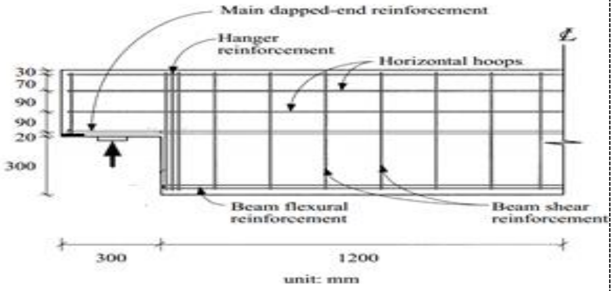


Figure 2. Reinforcement layout of modelled beam.

In case of modelling reinforced concrete beams, a perfect bond was assumed between steel and concrete elements and was achieved by assuring steel and concrete elements share common nodes in the discrete model. Mesh density is considered as one of the most important aspects of finite element modelling as due to strain gradient across an element, coarse meshing in complex areas of a structure may produce unreliable results. In modeling dapped-end beams, different meshing sizes were used in different locations, finer meshes were used in areas where higher stresses are expected to develop. In LS-DYNA, the most popular choice for modelling concrete in three dimensions is to use eight nodded hexahedral solid elements which has been found to be very efficient [12] are used in this study. Reinforcement steel and stirrups were simulated using beam and truss elements and all boundary condition parts were modeled using solid elements. To simulate behavior of reinforcement steel material in this study *MAT_PLASTIC_KINEMATIC (MAT_003) was used. For steel plates and cylinders used in modeling roller supports for the selected simply supported beam in addition to the steel impactor which represents the weight dropped as the external applied load was modelled as rigid material. Rigid elements are bypassed in the element processing where no storage is allocated for storing history variables; thus, the rigid material type is very cost efficient [13].

In order to capture the complex nature of concrete, different material models were used for simulating its behavior and Concrete Damage Rel.3 (Material 72R3) was found to be able to capture the behavior of the beam closely to the experimental behavior. The Hexahedron solid elements used in concrete modeling are considered as under-integrated elements with only one integration point, therefore defining hourglass model is needed in order to resist any undesirable hourglass modes. To control hourglass, a stiffness hourglass formulation was used. Stiffness forms generate hourglass forces proportional to components of nodal displacement contributing to hourglass modes. Different hourglass types and coefficients were used through different stages of simulations in order to decide the most suitable ones for the simulated beam as using inappropriate hourglass type or coefficient can be noticed on the results. Previous analyses and studies suggest that hourglass energy should not exceed 10% of the internal energy [12] for both entire system and each part of the system. In case of the whole system, internal energy was 17,442 J and hourglass energy was 593 J, hence, the hourglass energy was well below 10% of the internal energy. While, in case of the energy of concrete material part only, the hourglass energy was 581 J while internal energy 16,190 J which also shows it was satisfying meeting the condition. On the other hand, deflection time histories obtained from the experimental tests on rectangular beam under impact load and from simulation of the same beam using the previously elaborated techniques are given in Figure 3. The figure demonstrates that the modelling techniques, selected material models and boundary conditions have produced results significantly close to the experimental values.

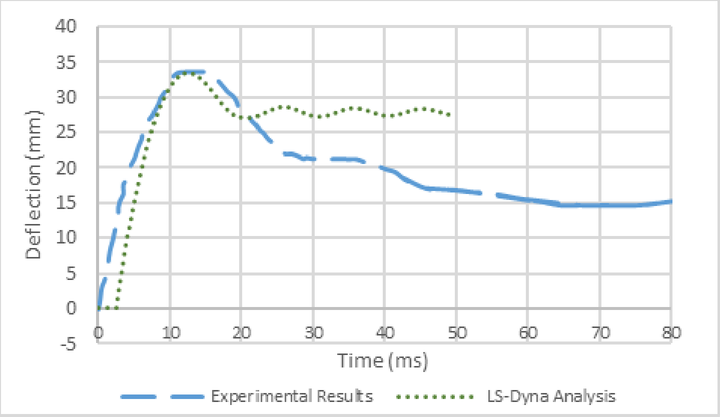


Figure 3. Deflection time-history comparison for model verification.

3. Finite Element Modeling

Main parameters tested in this study included main- and hanger-reinforcement layouts with different grades of concrete. This study aims to produce better understanding of the influence of various reinforcement layouts on the impact behavior of dapped-end beams. Reinforcement layouts varied in terms of the number of bars, diameter of bars and spacing between steel bars. Figure 4 shows different main dapped end reinforcement layouts, some reinforcement layouts had a very similar area of steel as the control beam and other had different ones. A total of 31 beam models were simulated in this research, all listed in Table 1.

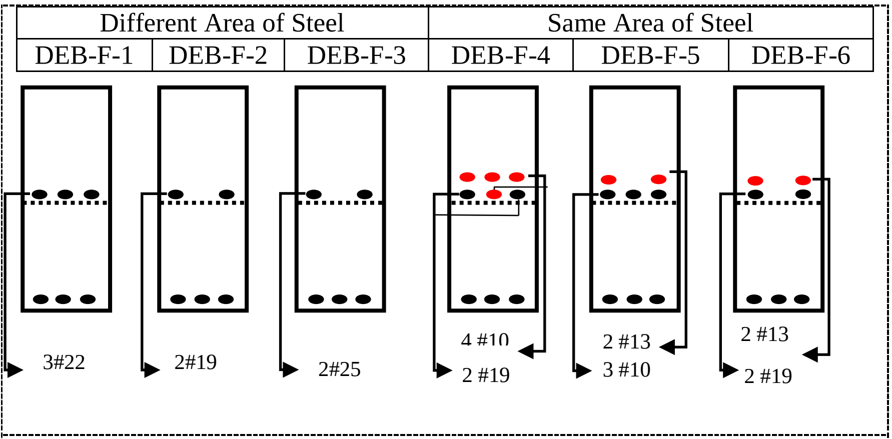


Figure 4. Simulated dapped-end main reinforcement layouts

Table 1. Symbols of dapped-end beam models along with all parameters variation

Main Parameter	Different Layout Notation		Model Symbol
Shear hanger reinforcement	3#10 @20 mm		DEB-S-1
	3#13 @20 mm		DEB-S-2
	5#10 @20 mm		DEB-S-3
	5#13 @20 mm		DEB-S-4
	2#13 @40 mm		DEB-S-5
	3#10 @40 mm		DEB-S-6
	3#16 @40 mm		DEB-S-7
Main dapped end flexural reinforcement	Different area of steel	3#22 (one layer)	DEB-F-1
		2#19 (one layer)	DEB-F-2
		2#25 (one layer)	DEB-F-3
	Same area of steel as control	2#19 and 4#10 (6 bars in two layers)	DEB-F-4
		3#16 and 2#13 (5 bars in two layers)	DEB-F-5
		2#19 and 2#13 (4 bars in two layers)	DEB-F-6
Concrete compressive strength and main dapped end reinforcement	3#22 (one layer)	f’c = 28 MPa, 40 MPa and 75 MPa	DEB-FcF-1a, 1b, 1c
	2#19 (one layer)		DEB-FcF-2a, 2b, 2c
	2#25 (one layer)		DEB-FcF-3a, 3b, 3c
	2#19 and 4#10 (6 bars in two layers)		DEB-FcF-4a, 4b, 4c
	3#16 and 2#13 (5 bars in two layers)		DEB-FcF-5a, 5b, 5c
	2#19 and 2#13 (4 bars in two layers)		DEB-FcF-6a, 6b, 6c

4. Results and Discussion

Concrete material model *MAT_CONCRETE_DAMAGE_REL3 doesn’t have the property of showing the crack propagation in the concrete. Thus, an additional material can be defined in order to show the damaged elements due to the applied load. *MAT_ADD_EROSION was defined and linked to the concrete material. Accordingly, some damaged beam models were viewed. Viewing the plastic strain contours helped in showing the expected crack pattern in the concrete Figure 5 shows the plastic strain contour for compressive strength of 40 MPa. According to plastic strain contours shown in Figure 5, it is clear that initial cracks will start to develop in the reentrant area nearer to the application of load and more concentrated in the upper area on the right side of the applied load. The area of continuance plastic strain in the concrete is located in the critical location where stress concentration is developed. Contours of plastic strain clearly indicted that the dapped-end beam has a shear failure mode. The formation of cracks for the control beam is shown in Figure 6. The crack patters also confirm the plastic strain distribution and failure initiation in the beam.

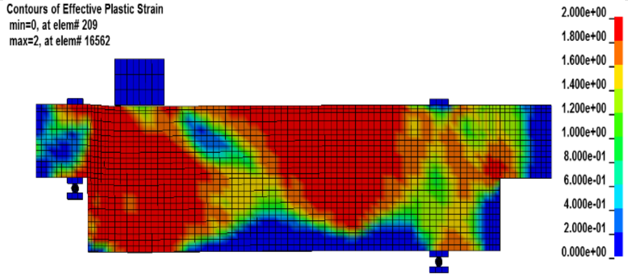


Figure 5. Contour of plastic strain under impact loading.

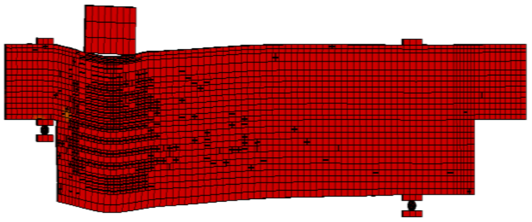
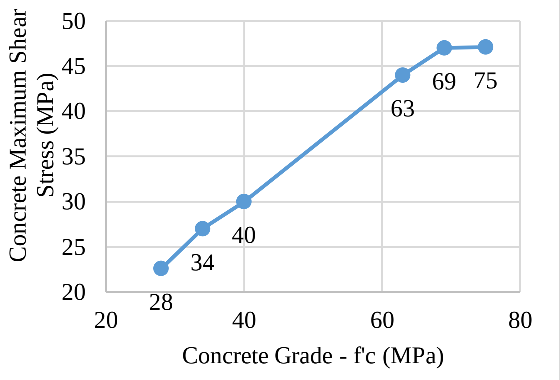


Figure 6. Crack pattern of the control beam obtained using erosion technique

The maximum shear stress was observed in the critical area of the dapped-end beam as expected. Generally, a very slight difference in shear stresses was noticed as detailing of both hanger and main dapped end reinforcements. Hanger reinforcement detailing didn't have much effect on the shear stress of high strength dapped end beams. The diameter of hanger reinforcement increased the shear strength of the high strength dapped end beam more than other factors of hanger reinforcement detailing did. On the other hand, concrete compressive strength had a greater effect on the shear strength of the dapped end beam under the applied impact load as shown in Figure 7. This agrees with the conclusion drawn by Lu *et al.* [2] that under static loads the shear strength of dapped end beams increases with the increase of concrete strength.

Stress-strain diagrams of main steel element for beam with different concrete compressive strengths are shown in Figure 8. When using a low strength concrete (28 and 40 MPa), steel showed a much rigid behavior than when compared to using a high strength concrete (70 and 75 MPa). This explains the fact that when lower strength concrete is used, steel is taking most of the load, while for higher grade of concrete, a large share of the load is handled by concrete.



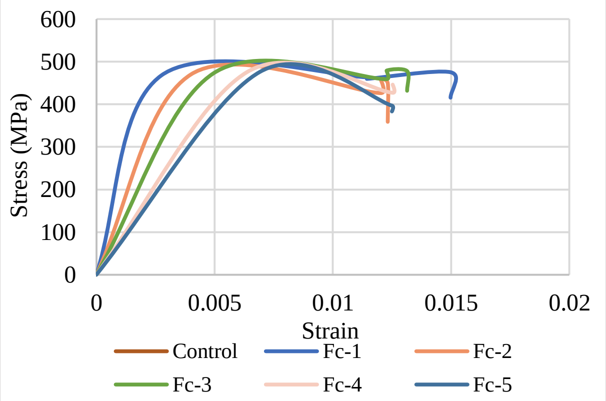


Figure 7. Effect of concrete compressive strength on the maximum shear stress.

Figure 8. Stress-strain diagrams of main dapped end steel element for different compressive strength changes

The detailing of hanger reinforcement was found to affect the rigidity of the main dapped end steel insignificantly. In all models' steel reached the yielding point when almost all of them had the same maximum value of stress under the same applied load. Moreover, in all cases steel experienced almost the same rigidity. Under the same applied load, compressive strength of concrete and detailing of main dapped end reinforcement steel had the major effect on the rigidity of main dapped end steel elements.

Lesser number of steel bars produced overstressed steel in case of DEB-F-2 and DEB-F-3 compared to other beams which indicates a higher chance of failure occurrence in the steel compared to other beams. Main dapped end steel was stressed similarly in all cases.

5. Conclusions

A parametric study was conducted on reinforced dapped-end beam models with different reinforcement layouts. The following points can be highlighted from the parametric study:

1. Under impact load, shear strength of DEBs increases as the concrete compressive strength increases.
2. Reinforcement layouts and concrete compressive strength didn't affect the failure mode of dapped end beams under impact load, all DEBs failed in shear.
3. Under the impact load all dapped end beams failed in shear as different parameters varied.
4. Cracks started to initiate in the re-entrant corner as expected due to the concentration of stresses.
5. Hanger and main dapped end reinforcement detailing affect sufficiently in crack control but not enhancement of shear strength for dapped-end beams under impact load.
6. Amount of provided main dapped end steel reinforcement has a significant impact on diagonal shear cracks and damage of beam under impact load.
7. Main dapped end steel reinforcement showed more ductile behavior in case of higher concrete compressive strengths. Similarly, more ductile behavior was noticed on main dapped end reinforcement steel bars as the provided area of steel increased.

6. References

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