Modelling of Dapped-End Beams under Dynamic Loading

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***Abstract*—The behavior of a reinforced concrete dapped-end beam under dynamic load is expected to vary from its behavior under static load. Although, many studies have been conducted on the performance of reinforced concrete rectangular beams under different types of dynamic loading, but in-depth investigations on the preformation of half-joints or dapped-end beams under impact loading are limited. Due to complexity and resource requirements for experimental study on half-joints, often numerical simulations are preferred. This study presents details of advanced finite element modelling of dapped end beams under impact loads to achieve a better understanding of their performance. This study includes modelling techniques using different constitutive material models for concrete to highlight the suitability of various concrete models to demonstrate the behavior of beams with half-joints. Verification results of the modelled dapped-end beam has been presented along with results showing behavior of modelled beam under different impact loads.**

***Index Terms*—finite element analysis, dapped-end beams, material modelling, impact loading**

I. Introduction

Dapped-end beams (DEBs) are identified as shear critical structural members based on vast research and studies completed on their behavior under static loading [1]. Extensive experimental and analytical studies have been conducted to investigate the behavior of dapped-end beams subjected to static loading [1]-[5]. In their applications, often dapped-end beams are exposed to dynamic loading. There is a clear gap in experimental studies on the behavior of dapped-end beams under dynamic loading conditions due to the difficulty and resource requirement involved to perform detailed studies on dapped-end beams under dynamic loading. Since, numerical simulations to study the DEB behavior under short duration dynamic load could be less resource intensive, there is a scope of development of realistic finite element models to capture realistic behavior of DEBs under dynamic loading.

In this research, advanced material models and modelling techniques were utilized to model and analyze the possible failure modes, strain histories for reinforcement bars and concrete and overall response time histories. Advanced modelling and model verification techniques were used to simulate realistic behavior of DEBs. The verified models were intended to be used for in-depth parametric study on dapped-end parameters and reinforcement details on the behavior of DEBs under dynamic loading. Non-linear finite element analysis to investigate crack propagation, failure mode and overall response were also targeted.

This research intends to enrich the literature on finite element modeling techniques of DEBs when subjected to dynamic load as well as demonstrates effectiveness of the proposed finite element model in capturing the realistic behavior of DEB under dynamic loading conditions.

II. Finite Element Modelling

Commercial package LS-DYNA which is highly capable of simulation of dynamic behavior of structural members was used to perform the structural response analysis. LS-DYNA is widely regarded explicit finite element program for efficient non-linear transient analysis of structures [6], [7]. LS-Prepost version 9.7.1 was used for the modelling. As no previous experimental study on the dynamic behavior of DEBs was found and since many studies have been completed on the behavior of rectangular beams under dynamic loading [8]-[12], verification of the modelling techniques and selected material models was performed by modelling a previously tested rectangular beam by Zhan *et al*. [9]. All the modelling approaches and material models were verified by comparing simulation results against the experimental results for rectangular beams. Once verified, same modeling techniques and approaches were followed in simulating DEBs.

A. Properties of Modeled Dapped End Beam

For this research, a reinforced concrete dapped-end beam previously tested under static was used for modelling. All the properties related to this beam were taken from Lu *et al*. [3]. The overall dimensions of the selected beam are shown in Fig. 1.

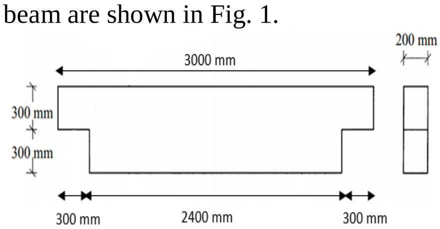

Figure 1. Dapped end beam configuration

Manuscript received January 20, 2017; revised April 19, 2017.

doi: 10.18178/ijmerr.6.3.242-247

The dapped ends were formed on opposite ends of a beam with a 200 mm × 600 mm cross-sectional beam, 3000 mm in length. The nibs are of a 300 mm in length and an overall depth of 300 mm; typical reinforcement details are shown in Fig. 2 [3]. Reinforcement properties and sizes are presented in Table I. The compressive strength of the concrete material was 69.2 MPa.

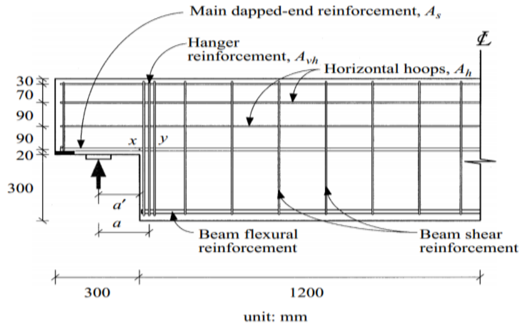

Figure 2. Reinforcement layout of simulated dapped-end beam

TABLE I. REINFORCMENET DETAILS OF SELECTED DAPPED-END BEAM

Main Dapped End Reinforcement			Horizontal Hoops			Hanger and Shear Reinforcement		
Bars	A_s (mm^2)	f_y (MPa)	Stirrups	A_h (mm^2)	f_{yh} (MPa)	Stirrups	A_{vh} (mm^2)	f_{yh} (MPa)
3#19	859	461	2#10	285	368	6#13	1520	430

B. Geometry and Meshing

A rectangular beam which was tested under dynamic load was modelled in LS-DYNA to select suitable mesh density, appropriate material models for reinforcement and concrete under dynamic loading conditions. Mesh sensitivity analysis was performed to choose suitable meshing scheme. Meshing schemes similar to the rectangular beam was also used for DEBs. Fig. 3 shows reinforcement placement using discrete model.

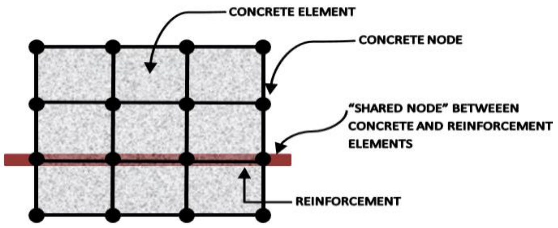

Figure 3. Representation of reinforcement in concrete using discrete model

Using LS-Prepost element and mesh options, 2D mesher was used initially to draw the plain concrete geometry and meshing of the beam. In case of modelling reinforced concrete beams, a full bond was assumed between steel and concrete elements and was achieved by both steel and concrete elements sharing 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. Too small mash sizes were also avoided to computational costs. As a dapped-end beam has some areas where stresses are expected to concentrate more compared to other areas of the beam, hence different meshing sizes were used in different locations, finer mesh was in areas where more stresses are expected to develop as shown in Fig. 4.

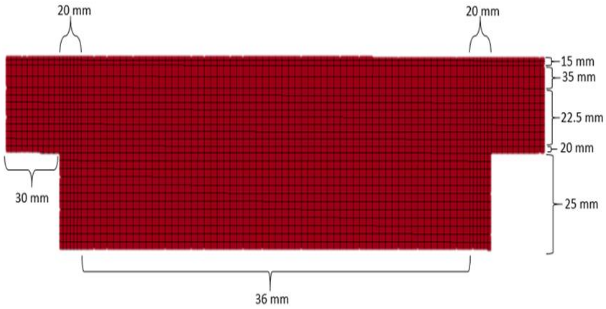

Figure 4. Meshing size variation along the entire dapped-end beam

C. Element Modeling

Finite element modelling of reinforced concrete is often challenging specially when under dynamic loading. In LS-DYNA, the most popular choice for modelling concrete in three dimensions is to use eight nodded hexahedral elements. Full details of the element formulation can be found in literature [13], [14]. It uses a reduced integration scheme (one-point integration) and has been found to be very efficient [15]. The presence of zero energy hourglass modes is considered to be the major disadvantage of using one point integration scheme. Accordingly, LS-DYNA has number of formulations for resisting undesirable hourglass modes. This will be further discussed later in this research.

Reinforcement steel and stirrups were simulated using beam and truss elements. Reinforcement bars were discretized with beam elements and stirrups with truss elements. A beam section properties were defined for the generation of reinforcement and stirrup steel. Beam section defines two node elements including 3D beams, trusses, 2D axisymmetric shells, and 2D plane strain beam elements. The interaction between the concrete solid elements and reinforcement beam elements has been modelled by merging their common nodes.

D. Hourglass Effect

Hourglass modes are non-physical modes of deformation that occur in under-integrated elements and produce no stress in the model. Since, hexahedron solid elements used in concrete modeling are under-integrated elements with only one integration point, there was a need to define hourglass model in order to resist any undesirable hourglass modes. To achieve hourglass control, a stiffness hourglass formulation was used. Stiffness forms generate hourglass forces proportional to components of nodal displacement contributing to hourglass modes.

At different stages of simulations, different hourglass types and coefficients were employed in the modeling. The effect of using inappropriate hourglass type or coefficient can be noticed on the results. In case of using stiffness hourglass forms, reducing the hourglass coefficient helped in reducing the stiffness of the beam and gave more realistic results. Choosing type 4 with coefficient 0.03 was found in this study to give reliable results.

Previous analyses and studies suggest that hourglass energy should not exceed 10% of the internal energy [15]. This should apply for both the entire system and each part of the system. Fig. 5 shows the hourglass energy values compared to internal energy in case of the whole system and concrete material part only. 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. Therefore, this check was fulfilled and hourglass type and coefficient were effectively appropriate.

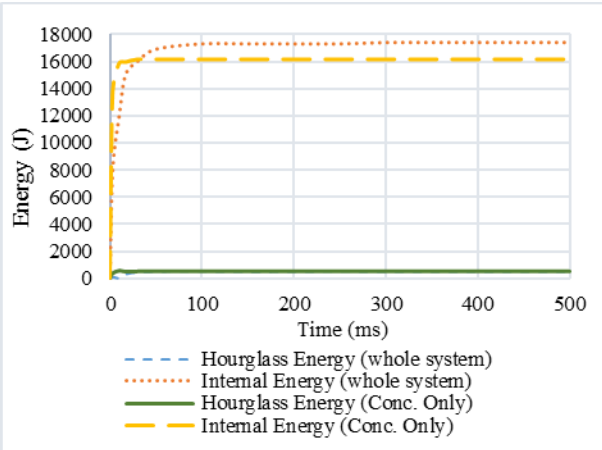

Figure 5. Internal and hourglass energies of both the whole system and concrete material only

E. *Material Modeling*

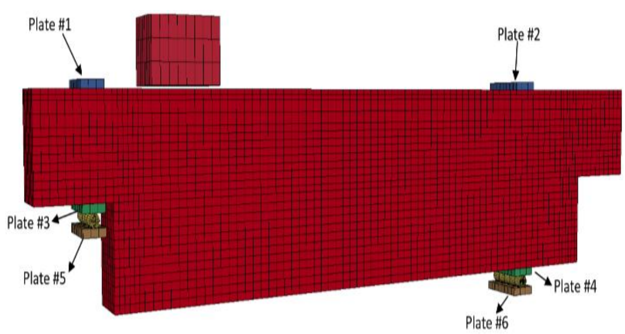

Figure 6. Dapped-end beam support system

LS-DYNA has vast library of material models which are able to simulate the behavior of different materials of interest. Steel plates and cylinders were used to model the roller supports for the selected simply supported beam. The steel impactor which represents the weight dropped as the external applied load was modelled with rigid material. The available rigid material in LS-DYNA provides an appropriate way of turning one or more parts of different element types into a rigid body. 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 [17]. LS_DYNA rigid material allows defining center of mass constrains both in displacement and rotation in three global directions. Details of the modelled supports are shown in Fig. 6.

For the rigid-material load impactor no constraints were defined. In *MAT_RIGID, Young's modulus, *E*, and Poisson's ratio, *v* are both used in determining sliding interface parameters if case there was a contact between the rigid body and another defined element in the model. According to Tavárez [7], in rigid material modeling, a high modulus would only cause a decrease in the time-step, causing an excessive run time. Similarly, in this research, different values of E were used in different models, and no effect was noticed on the behavior of the model. Therefore, in this modeling, the same realistic value of E = 2.0E11 Pa and a Poisson ration of 0.3 was used for the rigid material modeling in all simulations.

Integrating a material model which can simulate the realistic behavior of steel reinforcement in elastic and post-yielding region is considered less tedious compared to the heterogeneous concrete material. This is due to the isotropic nature of the steel reinforcement. There are many material models which can be used in simulating the behavior of a reinforcement steel material in material models library. The model used in this study was *MAT_PLASTIC_KINEMATIC (MAT_003). This model is suited to model isotropic and kinematic hardening plasticity with the option of including strain-rate effects. It is a very cost effective model and is available for beam (Hughes-Liu and Truss), shell, and solid elements [17].

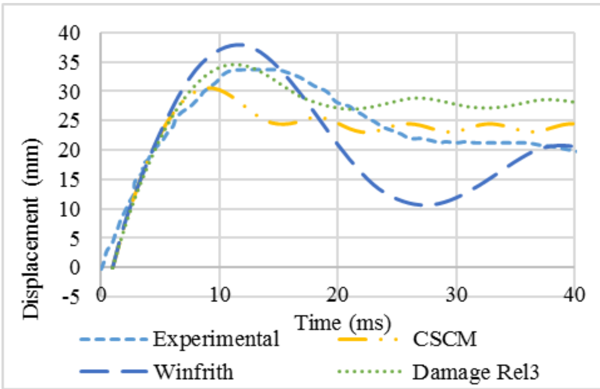

Figure 7. Deflection history comparison between different concrete material models

To capture the complex nature of concrete, a large number of constitutive models have been developed. For this research, three different material models were tested and compared to identify which of these material models was able to simulate the most accurate and realistic behavior of the RC beam. The concrete material models used the finite element analysis of reinforced concrete beams are Winfrith concrete (Material 84), Concrete damage Rel.3 (Material 72R3) and CSCM concrete (Material 159). In all three material models, strain-rate effect was taken into consideration. For material model 72R3, strain rate effect can be included as a strain rate vs. DIF curve which is defined according to each concrete compressive strength. While for materials Winfrith concrete (Material 84/85) and CSCM concrete (Material 159), strain-rate effects can be included or excluded by only activating or de-activating option in the material model card. A comparison in deflection-time history results obtained using three different concrete material models as are shown in Fig. 7.

F. Dynamic Increase Factor (DIF)

To incorporate the effect of strain-rate on material properties, the material curve requires the calculation of the strength enhancement factor, which is also known as the Dynamic Increase Factor (DIF). The dynamic behavior of concrete and concrete like materials are strain-rate dependent [18] and is expected to show increase in strength, strain capacity and fracture energy when exposed to impact loads.

Equations proposed by Malvar and Crawford [19] were used in determining the DIF for different values of concrete compressive strengths for various simulations. Strength enhancement values for concrete materials could be as high as 6 times in tension, and more than 2 in compression. While in reinforcing steel, it can be increased by more than 50% [19].

G. Boundary Conditions and Load Application

In order to simulate the behavior of the selected simply supported RC beam, total of six steel plates with a thickness of 25 mm where modeled as shown previously in Fig. 6. Two steel plates (#1 and #2) were at the top of the beam with a total restriction for rotations and displacements were provided in order to prevent the beam from bouncing off, similar to that done in the real test set up. Another two (#3 and #4) at the lower part of the beam, where only rotation around the X-Axis was allowed. The remaining two plates (#5 and #6) were modeled to hold the steel cylinder roller, where both along with the steel cylinders were restricted in all direction for both rotations and displacements.

The dropped weight was modeled by a rigid load box with a mass of 90 kg, and assigned an initial velocity of 20 m/s. The load box was modeled on a distance of 650 mm away from the left support.

III. Modeling Verification

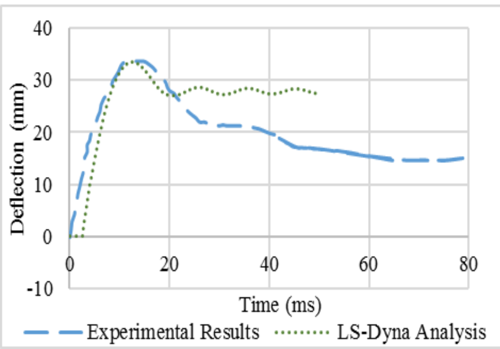

Figure 8. Load deflection curve for verification

Deflection time histories obtained from the test on rectangular beam under impact load and from simulation of that beam using the previously elaborated techniques are given in Fig. 8. The figure demonstrates that the modelling techniques, selected material models and boundary conditions have produced results significantly close to the experimental values.

IV. Parametric Study and Results

Using the verified simulated model, parametric studies can easily be performed to attain better understanding of the behavior of DEBs under dynamic load. For this research, some parameters such as diameter of bars, number of bars for both main dapped-end reinforcement and hanger reinforcement, concrete compressive strength, and value of load applied were investigated. Shear strength of the simulated dapped-end beam was observed, as different reinforcement schemes were used and different compressive strengths of concrete was also used. The effect of each parameter was observed by comparing a control model to other models.

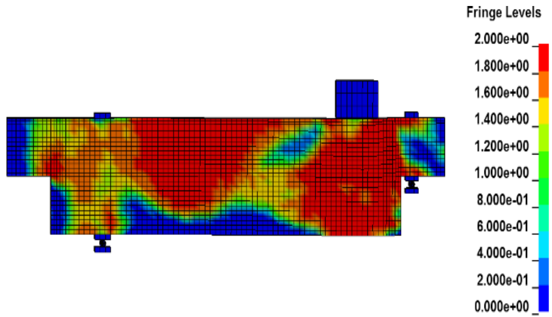

Figure 9. Plastic strain contours of dapped-end beam

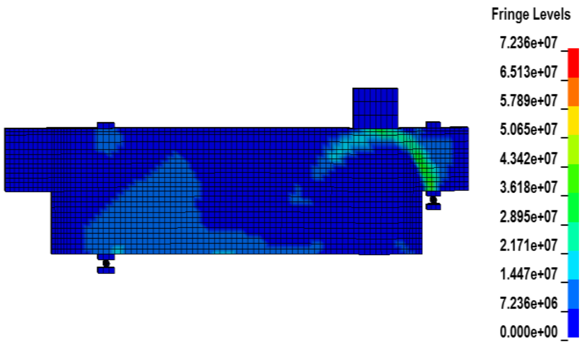

Figure 10. Maximum shear stress contours of dapped-end beam

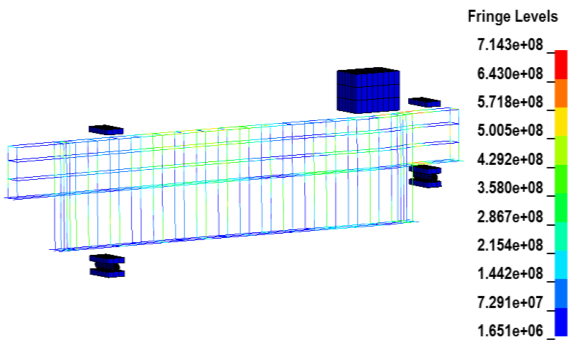

Figure 11. Effective (v-m) stresses contours of reinforcement layout of dapped-end beam

Contours of effective stresses, principal stresses, shear stresses, effective strains and stresses on any axis or plane for both concrete and steel material were obtained from the parametric study some representative results are shown in Fig. 9 to Fig. 16 to demonstrate the performance and ability of the simulated model of the dapped-end beam under impact loading.

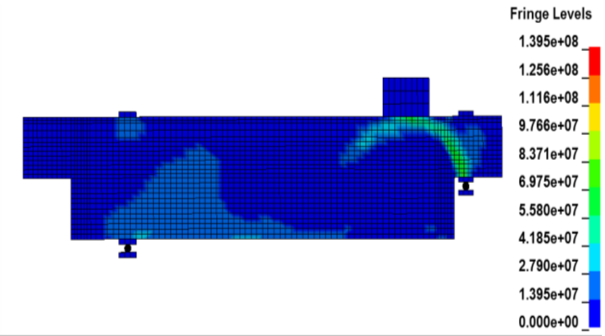

Figure 12. Effective (v-m) stresses contours of dapped-end beams

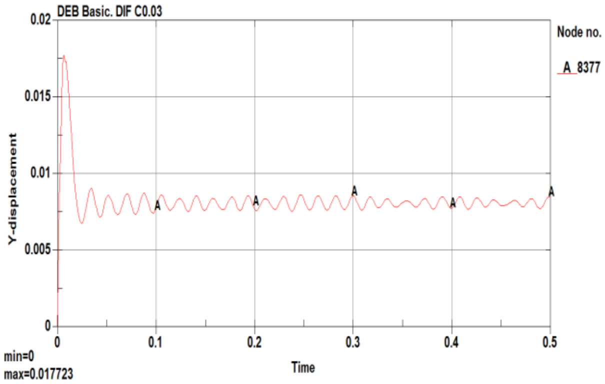

Figure 13. Maximum deflection curve of dapped end beam

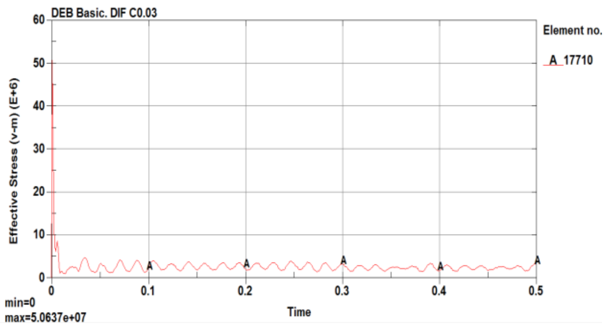

Figure 14. Effective stress (v-m) curve of desired concrete element of dapped-end beam

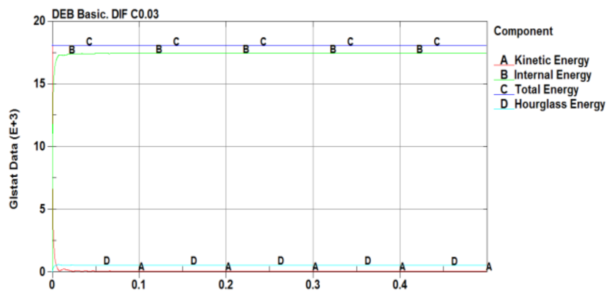

Figure 15. Kinetic, internal, total and hourglass energies of dapped end beam

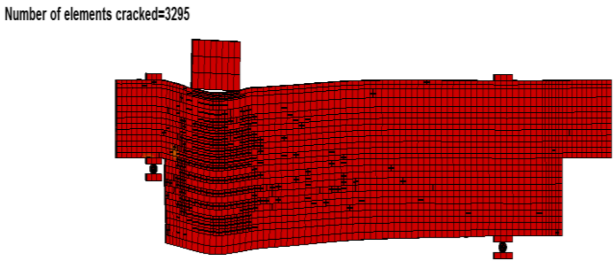

Figure 16. Crack pattern of dapped-end beam subjected to impact load

V. Conclusion

A three dimensional finite element model was developed to simulate the behavior of dapped-end RC beams under impact loading. Performance of the modelling techniques and selected material models have been verified using a previously experimented rectangular beam model since no previous tests were completed on dapped end beams under the same type of dynamic loading, the dapped end beam model was completed along with a parametric study, and the following conclusions were addressed:

1) The proposed FE modelling approach can be used to simulate and observe the behavior of dapped-end beams under impact loads, the verified model was also used to perform a parametric study.
2) As expected, behavior of simulated concrete material models was dependent on mesh sizes.
3) For the proposed mesh size in rectangular model, Concrete damage rel3 material model gave the most realistic deflection result compared to CSCM and Winfrith. While CSCM material model displayed a stiffer behavior compared to other models, and Winfrith model showed the most flexible simulation among the three material models.
4) Appropriate choice of hourglass type and coefficient is essential since it can affect the behavior of the simulated RC beam.
5) The completed FE model can produce deflection curves and stresses and strain of both steel and concrete and can also demonstrate the propagation of cracks in concrete.

Acknowledgment

The authors acknowledge the financial support provided by the Center on Sustainable Built Environment and the Office of Research at Abu Dhabi University under grant no C.C 19300075 to conduct this research.

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