Theory and Evaluation of Concrete Material Model 159

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Abstract

The roadside safety community supplements real world crash test data with LS-DYNA simulations performed on the computer. The accuracy of the simulations depends, in part, upon the material models that are formulated to simulate the behavior of the roadside structures and vehicle materials. One important roadside structural material is concrete. A comprehensive concrete material model was developed, implemented in the LS-DYNA finite element code, and evaluated for simulating the deformation and damage to reinforced concrete beams from dynamic impact. For ease of use, default material properties for concrete are incorporated into the model as a function of concrete compressive strength. Correlations with drop tower and bogie vehicle impact tests are used to evaluate the model and finalize the default material properties.

Introduction

Three million human injuries and 42,000 premature deaths occur annually as a result of motor vehicle crashes [1]. To help reduce this toll, the Federal Highway Administration (FHWA) has set a strategic goal to improve the safety of our nation's roadways. One way this is being accomplished is by expanding the use of the LS-DYNA finite element code [2] to replicate three-dimensional motor vehicle crashes into roadside safety structures. The objective is to make the structures more crashworthy to protect the vehicle occupants from serious injury. Roadside safety structures include bridge decks, barriers, and guardrails. One important bridge, barrier, and guardrail material is concrete (with reinforcement).

The goal of this research is to develop, implement into LS-DYNA, and evaluate a concrete material model that represents concrete used for roadside safety hardware testing. This paper reviews the evaluation of a concrete material model that APTEK developed and implemented into LS-DYNA as material model 159. This work is part of a coordinated effort sponsored by the FHWA and led by APTEK. The model was developed and evaluated by APTEK through correlations with dynamic reinforced concrete beam tests conducted by the Worcester Polytechnic Institute (WPI) and the Midwest Roadside Safety Facility (MWRSF). Additional evaluations (not reported here)

of pendulum-impacted bridge rails are underway and are being conducted by the Texas Transportation Institute (TTI).

Model Overview

The concrete model developed by APTEK is commonly referred to as a smooth or continuous surface "cap" model. Hence model 159 is implemented in keyword format as MAT_CSCM for Continuous Surface Cap Model. A smooth and continuous intersection is formulated between the failure surface and hardening cap, as shown in Figure 1. Here the failure/yield surface is plotted as shear strength versus pressure. The model is an extension of a simple cap model originally developed by Pelessone [3]. The model includes isotropic constitutive equations, yield and hardening surfaces, and damage formulations to simulate softening and modulus reduction. A rate effects formulation increases strength with strain rate. General discussions of these types of formulations are given in References [4,5,6]. Thorough details of the concrete model theory are being documented by APTEK in a manual titled User's Manual for LS-DYNA Concrete Model 159 [7]. This manual should be complete and available for use by the end of 2004. A concise theoretical description is available in the latest LS-DYNA User's Manual. An overview of the default material property scheme is given in the next section.

Concrete structures typically contain steel reinforcement. Steel reinforcement exhibits rate effects, and yields in a ductile manner until it breaks at an ultimate strain greater that about 20%. The reinforcement model plays an important role in modeling reinforced concrete behavior. Our approach is to explicitly model the reinforcement (beam elements) separate from the concrete (hex elements) using an elasto-plastic material model with yielding, hardening, rate effects, and plastic strain-based failure (such as MAT_PIECEWISE_LINEAR_PLASTICITY).

Default Material Properties

Ease of use is also an important consideration for the roadside safety community. Many users are experienced in performing LS-DYNA analyses, but are less experienced in material modeling and fitting procedures. Often, the user will lack the necessary time, data, and material modeling experience to accurately fit a set of material model parameters to data. The ability of a material model to simulate real world behavior not only depends on the theory of the material model, but on the fit of the material model to laboratory test data. Therefore, the model is being made easy to use by implementing a set of standardized material properties for use as default material properties.

Two methods for model input are available. One method is for the user to supply all input values for model parameters (MAT_CSCM). This includes up to 37 parameters that are fit to data, and 7 additional control parameters. The other method is to request default input values for model parameters (MAT_CSCM_CONCRETE). Default material model parameters are provided based on three input specifications: the unconfined compression strength (grade), the aggregate size, and the units. The unconfined compression strength affects all aspects of the fit, including stiffness, strength, hardening, and softening. The aggregate size primarily affects the brittleness of the softening behavior of the damage formulation. The default properties are recommended

for use with concrete with unconfined compressive strengths between about 20 and 58 MPa, and aggregate sizes between 8 and 24 mm. Emphasis for the default material properties and model formulation is the tensile and low confining pressure regimes typical of roadside safety applications.

Our approach for obtaining the suite of material properties is through correlations with the WPI and MWRSF tests, supplemented with recommendations in the CEB-FIP Model Code 1990 [8]. This code is a synthesis of research findings and contains a thorough section on concrete classification and constitutive relations. Various material properties, such as compressive and tensile strengths, stiffness, and fracture energy, are reported as a function of grade and aggregate size.

Test Data Overview

Evaluation of the model requires two general types of test data: basic material property data of plain concrete for determining input parameters to the model, and impact tests of reinforced concrete for evaluation of the model. To date, evaluation of the concrete model for roadside safety applications has primarily been accomplished through LS-DYNA correlations with two sets of reinforced concrete structural tests: drop tower and bogie vehicle impact tests. These tests are intended to produce failure conditions in the concrete that replicate the failure conditions in roadside safety applications.

Forty-seven dynamic drop tower tests were conducted by the WPI on 1/3rd scale beams. Drop tower tests allow for dynamic testing of simple concrete structures in a controlled, well-documented environment. Scaling was necessary to perform the tests in the indoor drop tower facility. The beams are approximate scale models of typical bridge rails or posts.

Three sets of 1524 mm long beams were tested in dynamic, four-point bending: over-reinforced, under-reinforced, and plain concrete beams. Calibration tests were conducted to determine the target impact kinetic energy at which the over-reinforced beams failed. Beam failure consisted of cracks running completely through the beam thickness, without pulverizing the beam. This target kinetic energy was held constant throughout all tests, while four combinations of impactor mass and velocity were tested. For all three types of tests, an increase in the impactor mass (with a corresponding reduction in impactor velocity) resulted in an increase in the beam deflection with deeper and wider cracks. The steel reinforcement did not break in any of the tests. All testing procedures, tests results, and data reduction are documented in Reference [9].

Three dynamic bogie vehicle impact tests were conducted by the MWRSF on full-scale beams. The 3.66-m (12 ft) reinforced concrete beams were simply supported and designed with longitudinal tensile reinforcement only. The bogie was set-up with an impact head to produce four-point bending. The test set-up is similar to a concrete bridge rail impact, yet significantly simplified in order to isolate the concrete behavior. All tests were conducted with a 2186.9 kg vehicle at speeds of 8.6, 15.9, and 33.1 km/hr. Observed damage consisted of flexural type cracks with beam rebound at low impact to inclined shear cracks and beam breakage (no rebound) at high impact. All testing procedures, tests results, and data reduction are documented in Reference [10].

To provide basic material property data for the analyses, WPI and MWRSF measured the quasi-static compressive strength of the concrete via cylinder compression tests, and the stress-displacement behavior of the rebar. WPI also conducted splitting tensile tests to measure the concrete tensile strength. The nominal concrete strength in the WPI tests was 27 MPa. The nominal concrete strength in the MWRSF tests was 46 MPa. The initial yield strength of the steel reinforcement was 456 MPa (WPI) and 462 MPa (MWRSF).

Concrete Model Simulations

Single Element Simulations
Single element simulations were performed to verify the implementation of concrete model, and to display the basic stress-displacement behavior of the model. Three sets of single element simulations are shown in Figure 2. The first two sets are for the direct pull (uniaxial tensile stress) and pure shear stress, in which the model behaves in a brittle manner. The second set is for uniaxial compression stress and triaxial compression combined into a single plot. The unconfined compressive strength is approximately ten times the unconfined tensile strength, in agreement with typical test data for concrete. Triaxial compression refers to tests or simulations in which the lateral confining pressure is held constant around a cylinder while the axial compression load quasi-statically increases. The concrete strength increases with confining pressure in the simulations, also in agreement with typical test data. The simulations shown are linear to the peak stress. A kinematic hardening formulation is optionally available to simulate pre-peak hardening (nonlinearity).

Single Material Simulations
Two sets of multi-element simulations were performed for plain concrete. These are quasi-static simulations of cylinders in tension and compression, and dynamic drop tower impact of beams. These simulations allow us to evaluate the behavior of the concrete model without the complicating effects of the steel reinforcement.

The cylinder analyzed is 12-inches long (304.8 mm) and 6-inches in diameter (152.4 mm). Loading conditions are direct pull (uniaxial tensile stress) and unconfined compression (uniaxial compression stress). These are achieved by applying a uniform constant velocity to the nodes at one end of the cylinder (tension) or to the end caps (compression). Damage modes simulated are those typically observed in cylinder tests: splitting of the cylinder in tension, and diagonal failure in compression (see Figure 3). Steel end caps, with slight friction between the cap and cylinder, are modeled in compression in order to simulate diagonal failure as observed by MWRSF in their compression tests. Idealized end conditions without friction or end constraint produce wedge-type failure, rather than diagonal failure, while laterally constrained ends produce two diagonals (damage in an X-shape).

Multi-element simulations of plain concrete beams were analyzed to check that the concrete model accurately predicts the damage mode observed in dynamic tests. One such simulation is compared with WPI test data in Figure 4. The 1524 mm long beam is impacted by two steel 32-mm diameter cylinders spaced 203 mm apart, as indicated by the arrows. The beam is supported on each end with 32-mm diameter cylinders. Tie-down straps are also placed around each beam at each end to prevent the beam from bouncing off the supports.

The measured and simulated damage mode is the formation of two major cracks on the tensile face of the beam. These cracks propagate towards the impactor points on the compressive face of the beam, ultimately splitting the beam into three distinct sections. The beam does not rebound. It eventually hits the bottom of the test fixture and breaks into multiple pieces (not simulated).

The colored fringes shown in all deformed configuration plots of this paper range from zero to one and indicate the level of damage calculated by the concrete model. A fringe value of zero indicates no damage, so concrete strength and stiffness are those originally specified as input values. A fringe value of one indicates maximum damage, in which the concrete strength and stiffness are reduced to zero.   Elements erode (are removed from the calculation and figure) when damage exceeds 0.99 and the maximum tensile strain exceeds a user-specified value (typically 0.10). An example fringe scale is given in Figure 3, which relates damage level to color.

Drop Tower Test Simulations
APTEK simulated the drop tower impact tests conducted by WPI using the LS-DYNA finite element code for over-reinforced and under-reinforced beams. In over-reinforced beams, the concrete crushes before the steel reinforcement yields. In under-reinforced beams, the steel reinforcement yields before the concrete crushes.   Over-reinforced beams are more brittle than under-reinforced beams, thus each type of beam exhibits different response modes.   The combined concrete and reinforcement models discussed in this paper accurately simulate these response modes.

Over-reinforced beam behavior is shown in Figure 5 for both the post-test beam and the LS-DYNA simulation.   Upon impact, in both the test and simulation, multiple cracks primarily initiate on the tensile face of the beam and propagate towards the compressive face.   Impact damage (crushing) is also visible beneath each impactor.   The beam rebounds and goes into reverse bending.

Under-reinforced beam behavior is shown in Figure 6 for both the post-test beam and the LS-DYNA simulation.   In both the test and simulation, two major cracks initiate on the tensile face of the beam and propagate towards the compressive face, essentially splitting the concrete into three sections.   Impact damage (crushing) is also visible beneath each impactor.   Little rebound occurs, although the reinforcement does not break.

In the over-reinforced beam tests, an accelerometer attached to the impactor measures acceleration that is integrated to produce velocity and displacement histories. One average displacement history (solid line) is shown in Figure 7 for comparison with the LS-DYNA calculated history (dashed line).   Good agreement is obtained for the initial stiffness and peak deflection. No accelerometer measurements are available for the under-reinforced and plain beams, although high-speed video indicates that peak displacements for the under-reinforced beams are about five times larger than those of the over-reinforced beams.   Such differences between under-reinforced and over-reinforced beam behavior are accurately simulated by the concrete and reinforcement models (see Figure 7).   Parameter studies are underway to adjust the input values (concrete and reinforcement) to improve the correlations.

Bogie Vehicle Impact Test Simulations

APTEK simulated the bogie impact tests conducted by the MWRSF using the LS-DYNA finite element code. Deformed configurations for the high velocity impact test are shown in Figures 8. Each result shown is conducted with different input parameter values. This demonstrates that the damage mode varies with input parameter value selection. The deformed configuration of the high velocity test and simulation is inclined shear cracks in the vicinity of the impact cylinders, plus peeling away of the concrete cover from the reinforcement on the tensile face of the beam. The deformed configuration of the low velocity test (not shown) is similar to that of the 1/3-scale WPI tests of over-reinforced concrete beams previously shown in Figure 5. This is because the WPI test beams are approximate scaled versions of the MWRSF test beams. The low velocity impact beam exhibits substantial cracking, but retains its integrity and rebounds.

Displacement history comparisons are shown in Figure 9 for the low and high velocity tests and simulations. Solid lines are the data, dashed lines are the simulations. Histories for both the beam and bogie vehicle are given at low velocity, because the vehicle separates from the beam upon rebound. The simulations accurately calculate the displacement histories through rebound. Some discrepancy exists following rebound at low velocity, in which the simulated beam and vehicle rebound more significantly than during the test. The source of this discrepancy is under investigation.

Summary

A concrete material model was developed and implemented into the LS-DYNA code as material mode 159. Although it was developed for roadside safety applications, it is a general-purpose model that can be used for most any application. The model was evaluated through correlations with reinforced concrete beam data from 1/3-scale drop tower and full-scale dynamic bogie impact tests. The model accurately simulates the displacement history and damage modes observed in these tests. Additional correlations are planned to include concrete bridge rails impacted by bogie pendulums. Documentation is planned to include a manual with a user's guide, theoretical section, and example problems, as well as an evaluation report.

Acknowledgments

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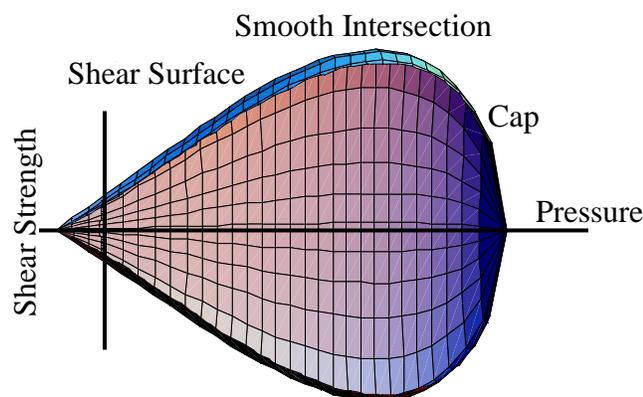
Figure 1.   General shapes of the concrete model shear failure and cap hardening surfaces in two dimensions.

(a) Tension and shear.   (b) Compression.
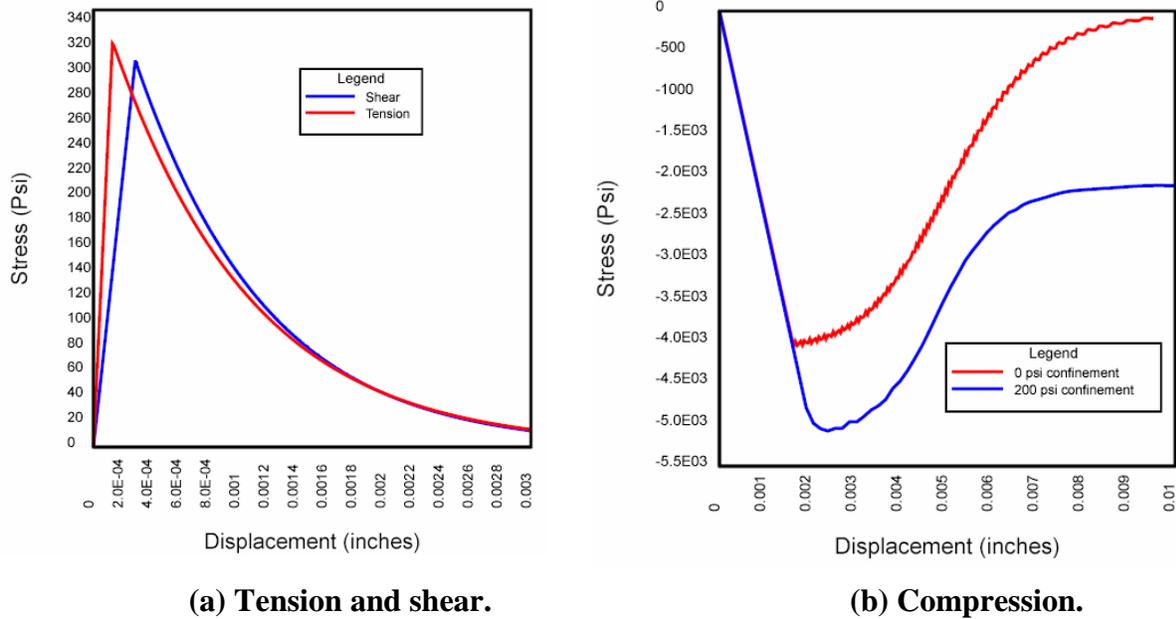
Figure 2. Typical stress-displacement behavior of the concrete model in single element simulations of uniaxial stress (tension, shear, and compression) and triaxial compression.

(a) Tension.   (b) Compression.   (c) Fringe scale.
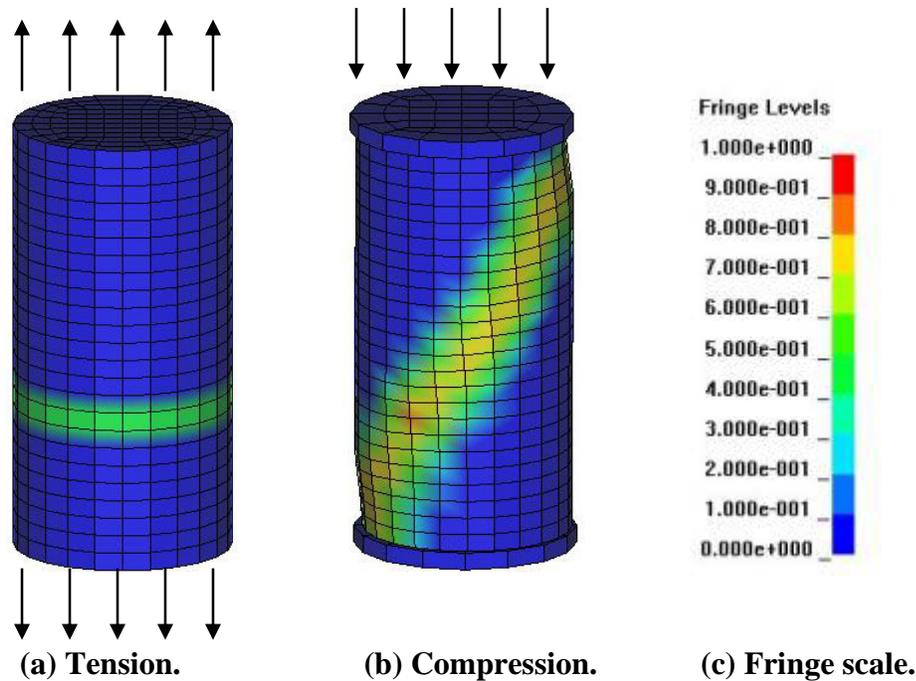
Figure 3. Realistic damage modes are simulated in concrete cylinders loaded in tension and compression.
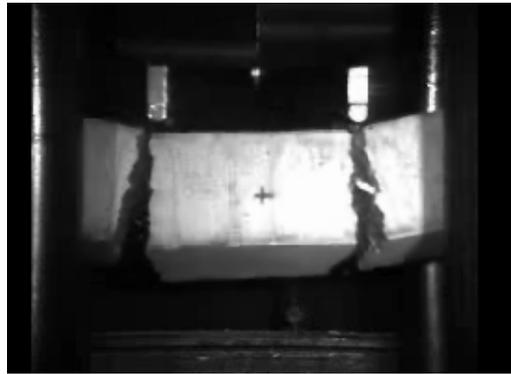
(a) Plain concrete test specimen.
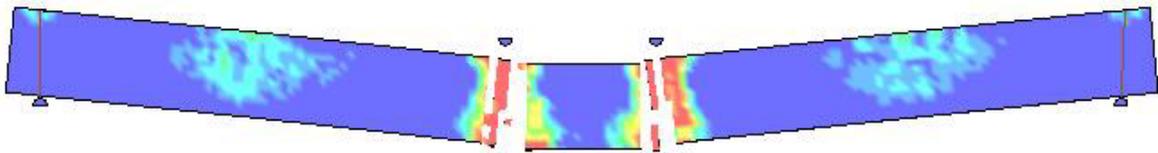
(b) LS-DYNA simulation.

Figure 4. The plain concrete beam breaks into three large pieces before impacting the bottom of the test fixture.
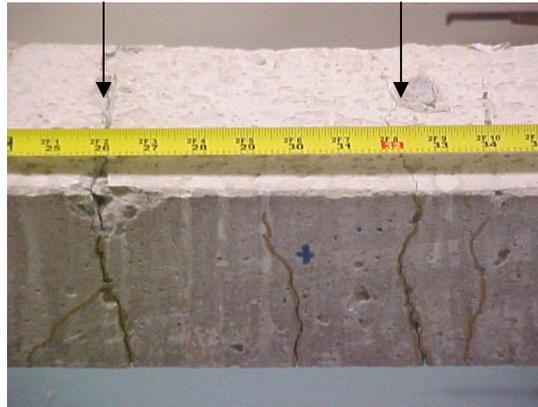
(a) Over-reinforced concrete test specimen in impact regime.
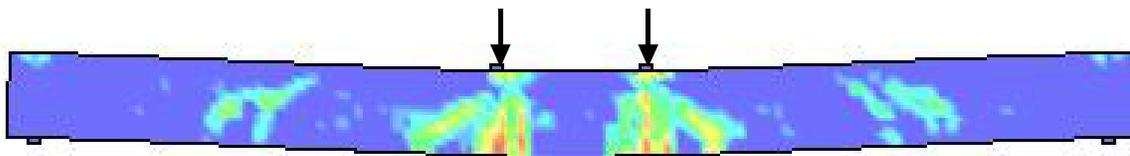
(b) LS-DYNA simulation at peak deflection.

Figure 5. The over-reinforced concrete beam has localized tensile cracks and concrete crushing in the impactor regime.

(a) Under-reinforced test specimen.
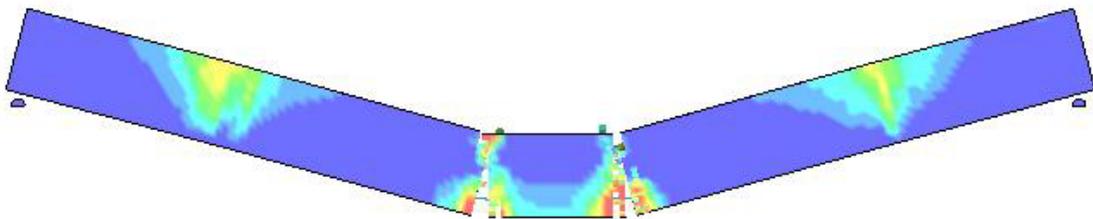
(b) LS-DYNA simulation.

Figure 6. The damage mode of the under-reinforced beam specimen is two major cracks beneath the impactor points, without rebar breakage.
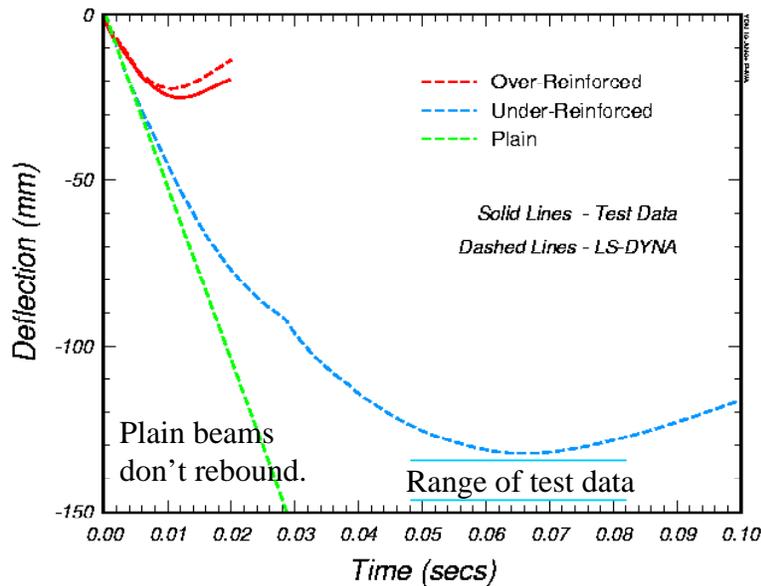
Figure 7.   Good displacement history and peak deflection comparisons of LS-DYNA drop tower impact simulations with test data for concrete beams.
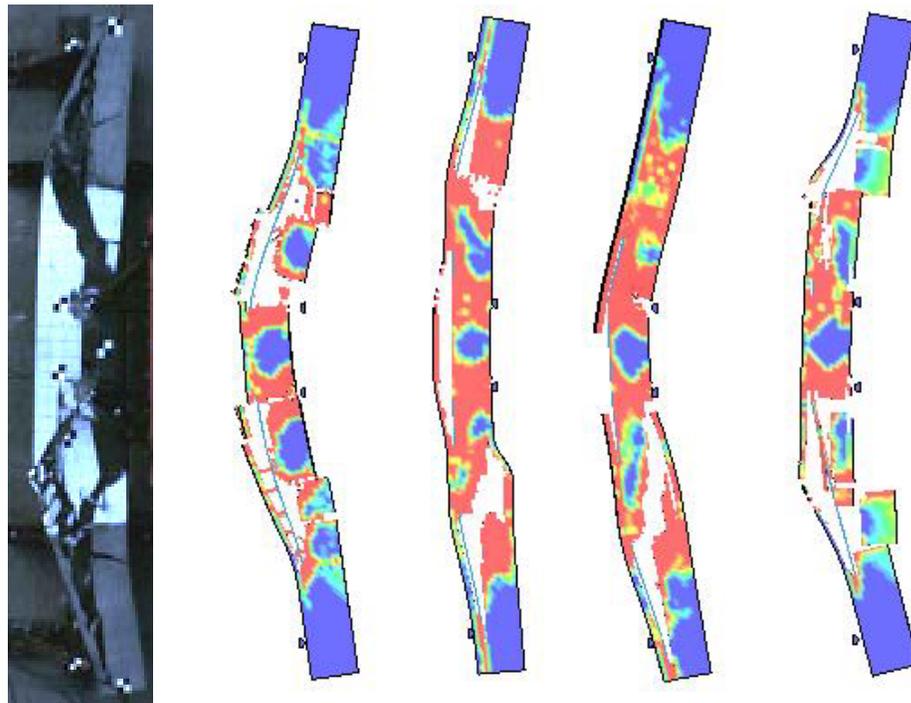
(a) Test specimen.   (b) Various LS-DYNA simulations.

Figure 8. These LS-DYNA calculations simulate the severe damage observed in the bogie vehicle impact test conducted at 33.1 km/hr.
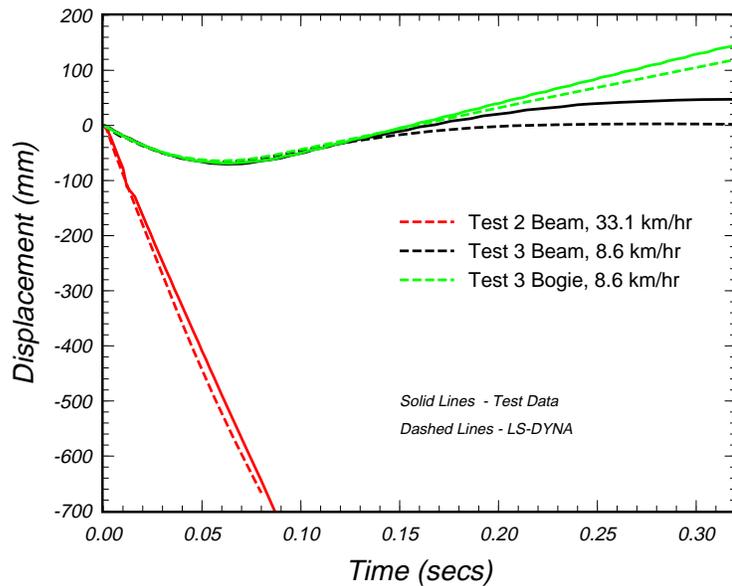
Figure 9. The displacement histories from the LS-DYNA bogie vehicle impact simulations compare well with the test data.