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OVERVIEW OF CRASH AND IMPACT ANALYSIS AT LAWRENCE LIVERMORE NATIONAL LABORATORY

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ABSTRACT

This work provides a brief overview of past and ongoing efforts at Lawrence Livermore National Laboratory (LLNL) in the area of finite-element modeling of crash and impact problems. The process has been one of evolution in several respects. One aspect of the evolution has been the continual upgrading and refinement of the DYNA, NIKE, and TOPAZ family of finite-element codes. The major missions of these codes involve problems where the dominant factors are high-rate dynamics, quasi-statics, and heat transfer, respectively. However, analysis of a total event, whether it be a shipping container drop or an automobile/barrier collision, may require use or coupling or two or more of these codes. Along with refinements in speed, contact capability, and element technology, material model complexity continues to evolve as more detail is demanded from the analyses. A more recent evolution has involved the mix of problems addressed at LLNL and the direction of the technology thrusts. A pronounced increase in collaborative efforts with the civilian and private sector has resulted in a mix of complex problems involving synergism between weapons applications (shipping container, earth penetrator, missile carrier, ship hull damage) and a more broad base of problems such as vehicle impacts as discussed herein.

INTRODUCTION AND BACKGROUND

Since the mid-1970's, Lawrence Livermore National Laboratory (LLNL) has been heavily involved in the development and application of nonlinear finite-element codes for large deformations of structural materials. The result has been an integrated suite of codes for multi-purpose applications. These include DYNA (both DYNA2D and DYNA3D) for the study of explicit transient dynamics problems of short-duration problems (typically fractions of a second), NIKE (2D and 3D) for the study of long-duration or quasi-static mechanics, and TOPAZ (2D and 3D) for thermal analysis. Together, the codes form a unique suite of tools that can be coupled yet are individually highly efficient and effective on their class of problem.

At LLNL, one of the major traditional roles has been and continues to be the study of weapons design, production, transport, and effects. It is in such studies that much of the work at LLNL has been performed in the past. These applications of the LLNL code suite have included studies of shipping container impact, damage, and risk analysis. From this work, improved designs for both impact and fire resistance have emerged. Impact analyses have also been performed using the NIKE and DYNA codes resulting in improved understanding of penetrator design and performance. Interestingly, the same material models used for that purpose are used successfully to analyze High Energy Rate Forging (HERF) processes to make raw forgings for our production parts.

Recently, the state of the art in our code suite has advanced in part due to applications in the civilian and commercial sector. This involves refining and improving the capability of DYNA and NIKE to handle crash and impact effects on automotive, air, and rail safety. We are working on several collaborative programs with government and industry to leverage our developments in defense and simultaneously advance the accuracy and speed of automotive crash analyses, and to establish the limits of classes of problems that can run on today's high-performance workstations. We have obtained good correlations with test data in studies of vehicular crash events at 100km/hr or less, and plan to extend our studies to higher velocities.

WEAPONS SAFETY IMPACT ANALYSES

LLNL research on container crashworthiness spans three decades. We have modeled drums used to protect radioactive material, a protective cage for the air transport of nuclear weapons, the hull of a submarine, and scores of other structures and vessels used for diverse purposes. To evaluate the detailed structural response of a storage, shipping, or containment structure in the event of an impact with some other object, we must consider many factors including container geometry, mass of the impacting body, mechanical properties of the materials, and impact velocity. Additional requirements include reducing the weight of the package and evaluating heat dissipation, fire hazard, or the possibility of combustion during various accident scenarios.

The illustration shows the deformed shapes of a mesh constructed to model the inner containment vessel of the UC-609 shipping container (Kay, 1993). This shipping package was developed to transport tritium payloads, and its design specifications required that it remain intact and sealed after being dropped nearly 10 meters onto an unyielding surface. We evaluated two drop scenarios: a top-down impact, and a top-corner impact. After simulating the responses of the container with DYNA3D, we compared our predicted results with actual test results. Whereas our calculations predicted some structural damage, we found no failure of the inner primary containment vessel for both drop configurations and no rupture of the outer drum. The top-corner simulation, which yielded greater damage to the primary containment vessel, predicted a crush height of 12 cm.; the experimentally measured crush was 12.7 cm. under the same impact conditions. The agreement was thus within about 5.5%. In many cases, the results of our impact analyses point to both benefits and liabilities of a particular design.

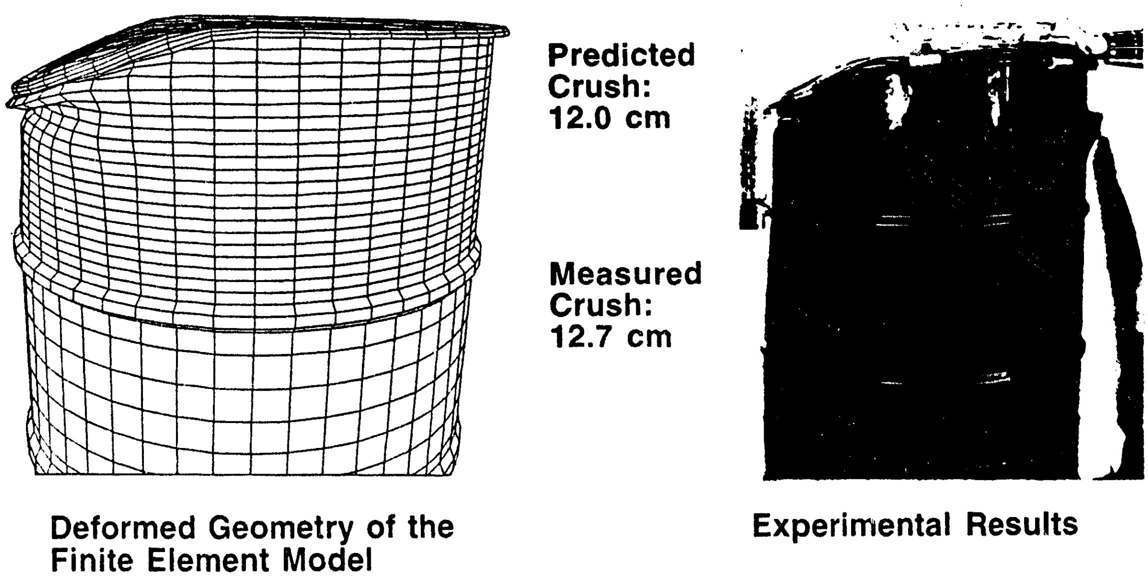
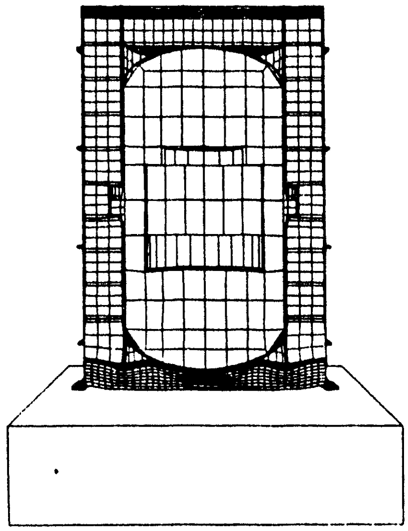
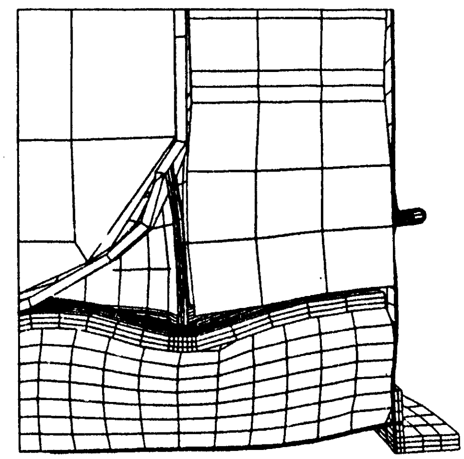


FIG. 1: FINITE-ELEMENT PREDICTION AND EXPERIMENTAL TEST IMPACT OF THE UC-609 SHIPPING CONTAINER.

Similar analyses have been performed on other shipping containers, such as the DT-20 design first studied in (Logan and Lovejoy, 1991). In a subsequent analysis shown in Fig. 2, comparison of finite-element model predictions and subsequent drop test data again shows good agreement. The interior detail of this design is shown in Fig. 2, which includes crushable packing material stacked in layers between plywood plates. These surround an open-ended steel cylinder, inside of which sits a stainless steel sealed can. The can contains aluminum support structures necessary to hold the payload confined. In fact, we have designed and analyzed containers where the entire inner structure is an aluminum spaceframe, as described elsewhere (McMichael, 1993). During the DT-20 impact considered here, the crushable thermal insulation and plywood deform, with some deformation to the inner stainless can as well, as shown in the detail of Fig. 2. However, both the DYNA3D prediction and experimental test showed survival of the inner can, with predicted plastic deformation of 3.9 cm. in an end-on drop, versus a measured deformation of 3.8 cm. in the experimental test.



Deformed Geometry of the Finite Element Model.



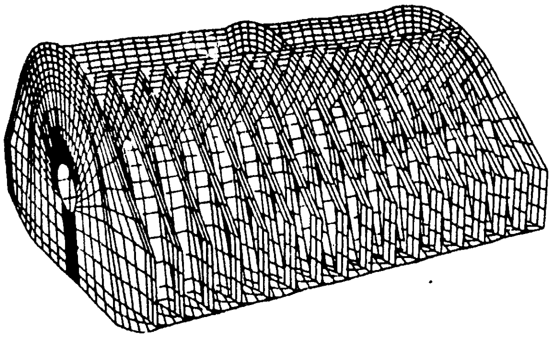
Detail of the deformed geometry near the drum flange.

FIG. 2: ANALYSIS OF THE DT-20 CONTAINER IN AN END-ON DROP. PREDICTED CRUSH DISTANCE AGREES WELL WITH TEST DATA.

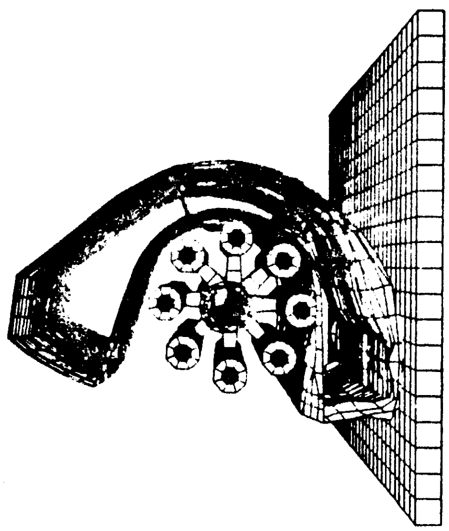
Of continuing importance is the survivability of weapon systems during a crash or accident. One key to such studies is an understanding of the mitigating effect of the surrounding containers on the environment seen by the weapon itself. The study illustrated in Fig. 3 was a proof-of-concept analysis performed four years ago to demonstrate that detailed crash calculations were within our analysis capabilities, and to provide some qualitatively correct insight into issues during impact into an aircraft weapons bay. The environment for the launcher was constructed with LLNL's mesh generators and is shown at the top of Fig. 3. The outer skin of the aircraft has been removed to show fuselage ribs and longerons. The subsequent DYNA3D analysis shown in the lower portion of Fig. 3 required 80 minutes of CPU on the Cray Y/MP to illustrate the effect of the airframe being struck from the side by a rigid object at 38 m/sec. In the deformed geometry view, the fuselage ribs and bulkheads have been removed to show the missile carrier payload on impact. The acceleration time history is shown at the right of Fig. 3 for locations near the warheads in four of the missiles. This informative figure shows all missiles experiencing the same environment for the first 7 ms of the impact. After that, the missile at 3 o'clock contacts the inner skin of the bomb bay and receives additional high frequency loading. This relatively slight increase continues until about 10 ms when the same missile contacts the intermediate bulkhead. The massive bulkhead provides a direct load path to the rigid wall representing the striking object. Large accelerations result and continue until about t=17 ms when contact is broken off. Since this analysis was only intended to explore the qualitative events occurring, the values of the accelerations shown are not as important as the relative histories of each of the four missiles followed ; only the 3 o'clock missile suffers a severe history due to its contact with the bulkhead. Problems like this can be designed out prior to conducting an expensive test or even knowing the quantitative level of the impact accelerations.

EFFECTS ANALYSES: SHIP DECK AND SUBMARINE HULL IMPACTS

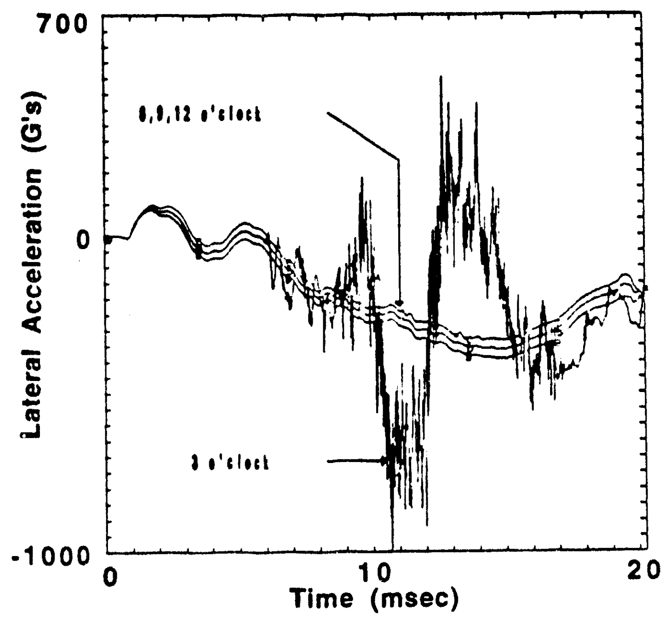
Accidental scenarios such as those above are by no means the only incidents which may be explored using finite-element technology. As part of one of our traditional missions of weapons design, we have analyzed countless penetrators for various applications. An example is illustrated in Fig. 4, with an obvious parallel to the study of crashworthiness of tomorrow's lightweight automobiles. Shown is a carbon fiber epoxy composite penetrator with a 4340 steel nose piece impacting 0.6 cm. thick structural steel plate similar to some ship deck materials. This problem was modeled using both the implicit NIKE2D code (Engelmann, 1991) and the DYNA3D code as well. Extensive calibrations were performed using rate-dependent material models to capture the correct peak loads and load-time histories in these drop tower impacts, which covered the velocity range from 3 m/sec to 30 m/sec. On obtaining a good model of target response, the goal was to conduct predictive exercises to determine the onset of failure in the fiber composite. The onset of failures such as shown in the experimental test on the right was indeed predicted by the simulations. Our predictions in this case used a simple strain to failure criterion for the laminate in the carbon/epoxy case. The compressive strain to failure was set at -0.01, or 1% strain in compression ; this invariably occurs in the axial direction. The actual strain to failure envelope for these materials is in general multiaxial (Groves et al. 1991), and indeed the progression of failure in Fig. 4 shows a hoop component splitting that progressed after the initial axial compressive failure. We are working on methodologies to model the progression of composite crush, thus capturing the load-time history needed for crashworthiness studies using these materials.



forward intermediate fuselage model



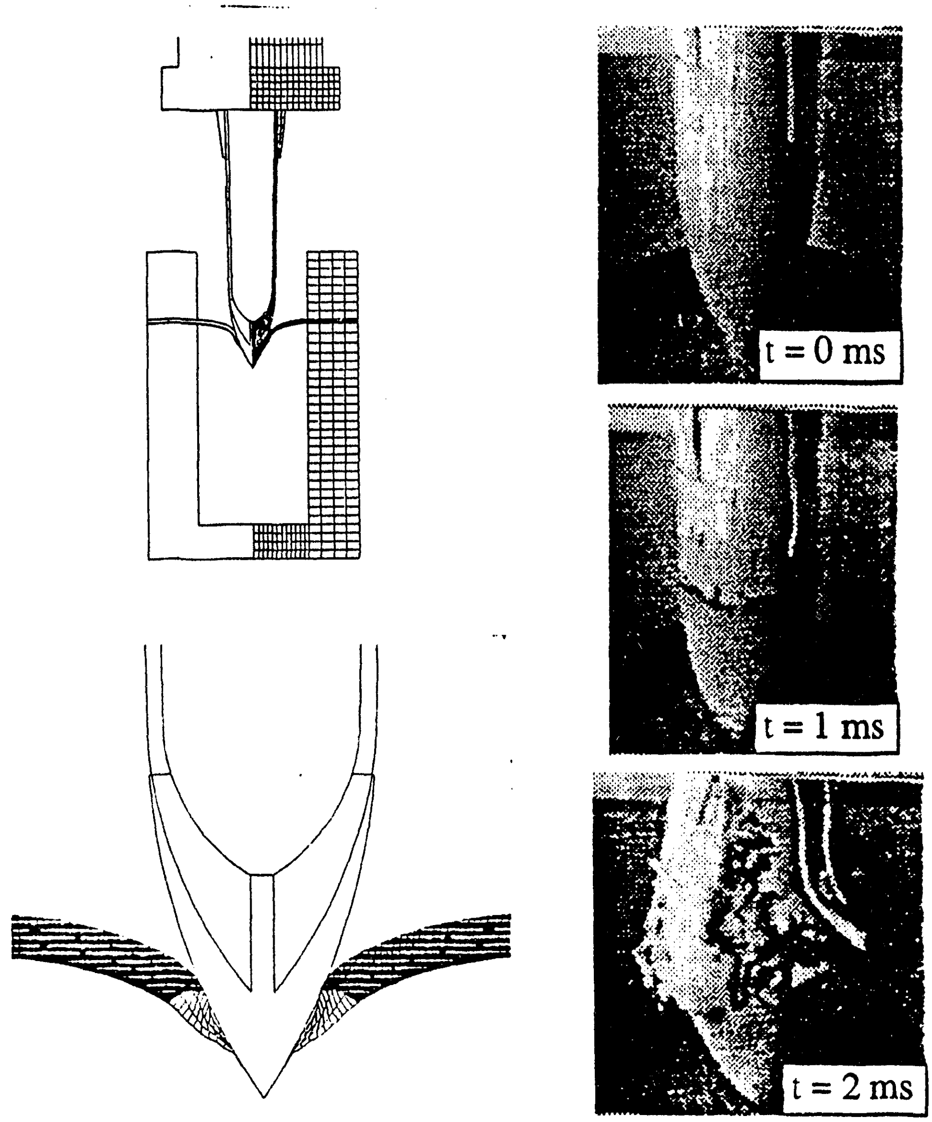
deformed geometry t=20 ms



acceleration profile

FIG. 3. AIRCRAFT WEAPONS BAY WITH MISSILE CARRIER ON IMPACT AT 38 M/SEC WITH A RIGID SURFACE (LOWER LEFT). ACCELERATIONS OF THE WARHEAD PACKAGES CARRIED ARE ALL SIMILAR EXCEPT FOR THE MISSILE AT 3 O'CLOCK AS DISCUSSED.

Recently, a material model that employs the well-known concept (Keeler, 1968) of the Forming Limit Diagram (FLD) has been implemented in DYNA3D (Logan, 1993). In addition to the traditional sheet metal forming applications, the model has proved useful in correctly capturing the features of impact and failure problems where multiaxial loadings influence the failure phenomena. Fig. 5 illustrates the basic point regarding failure under these conditions. In a sheet (or shell-like structure), the deformation of a grid circle into an ellipse can be used to determine the likely tearing level as measured by the major strain or stretch. The level achieved depends on loading in the orthogonal direction (the minor strain).The resulting FLD usually takes on a 'V' shape as shown in Fig. 5. For most metals, the minimum major strain to failure occurs in plane-strain tension. The failure level is somewhat higher in biaxial tension, and higher still in uniaxial tension. If a scalar criterion such as effective strain or plastic work is used, the calculated FLD would actually be inverted to what is normally observed. Strain to failure where the major strain is uniaxial tension will be predicted correctly, whereas failure predictions in biaxial tension will be pessimistic,, and failures in plane strain tension may be missed altogether.



Finite element model **High speed video**

FIG. 4. NIKE2D MODEL OF CARBON FIBER COMPOSITE PENETRATOR IMPACT. HIGH SPEED VIDEO OF LLNL EXPERIMENTAL TEST IS SHOWN AT RIGHT. NIKE2D OR DYNA3D ARE USED TO PREDICT ONSET OF FAILURE.

An example of the necessity for a model such as FLD in failure analysis of shell problems is shown in Fig. 6. The problem illustrates the effect of an underwater blast on submarine hull ribs tearing away from the hull. The white (unshaded) areas in the gray-shaded rib elements indicate areas where tearing is predicted as a result of the deformations. There are two such areas, one at about 5 o'clock and the other further back in the structure at about 4 o'clock. This latter area of failure is completely missed if scalar effective strain is used, and yet it is observed experimentally. Fig. 7 is a histogram of the scalar effective strain at which the elements in this problem failed. In our scalar effective strain-to-failure analysis, we used a value of about 0.17 ; the group of elements predicted by FLD to fail at less than this scalar value represents the region of failure in Fig. 6 that was not captured when using the scalar method. In contrast, if we use a scalar value of 0.17, we will prematurely predict failure in those elements that held out to a higher scalar value due to their multiaxial strain path. In fact, significant errors will occur no matter what scalar value is chosen in this problem. We have observed similar trends in sheet forming analysis as have many others.

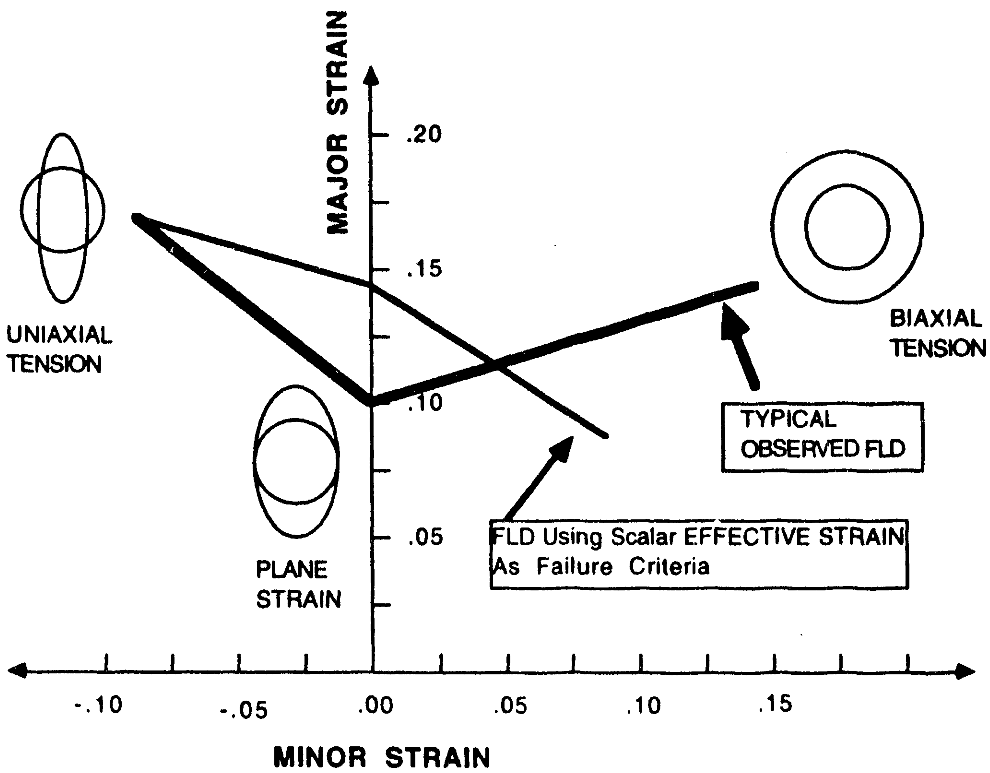


FIG. 5. THE TRADITIONAL FORMING LIMIT DIAGRAM (FLD) FAILURE ENVELOPE, AND THE INCORRECTNESS OF THE DIAGRAM IMPLICITLY USED WHEN SCALAR EFFECTIVE STRAIN IS USED AS A FAILURE MEASURE.

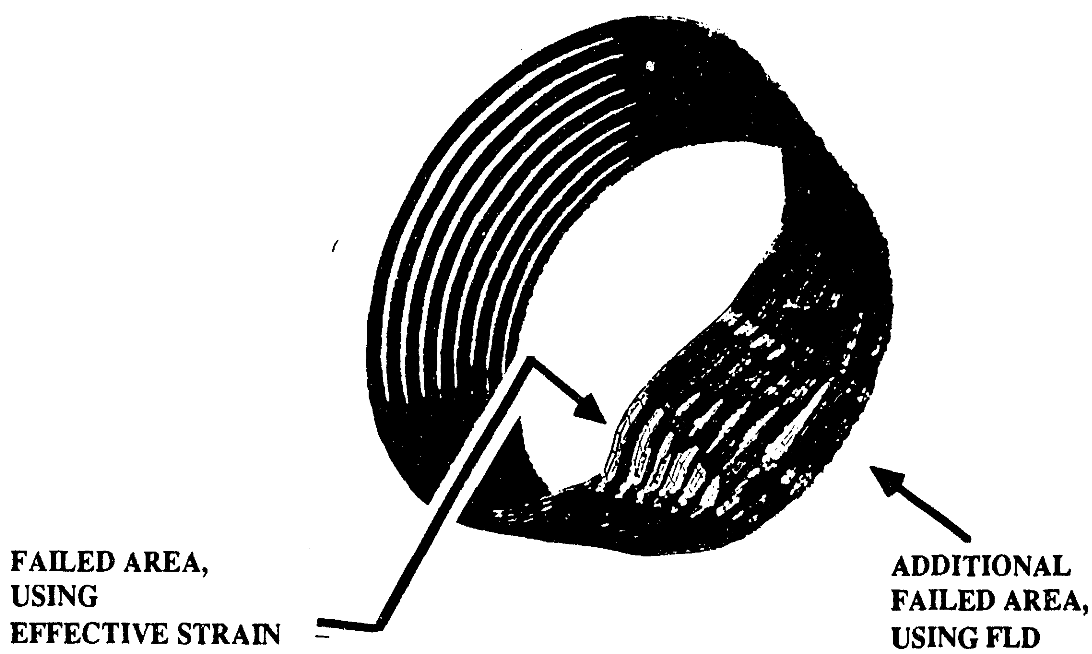


FIG. 6. AREAS OF PLASTIC STRAIN IN DAMAGE OF SUBMARINE HULL STRUCTURE DUE TO UNDERWATER BLAST. WHITE (UNSHADED) AREAS REPRESENT FAILURE REGIONS PREDICTED USING FLD METHOD.

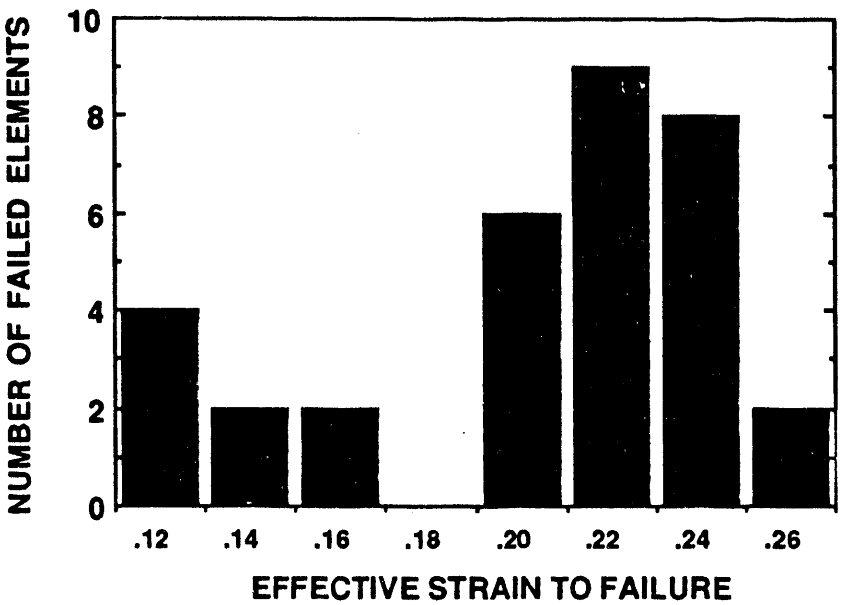


FIG. 7. HISTOGRAM OF SCALAR EFFECTIVE STRAIN TO FAILURE AS PREDICTED USING THE FLD MATERIAL MODEL IN DYNA3D. SPREAD IS MORE THAN A FACTOR OF TWO, ALL BUT PRECLUDING THE USE OF A SCALAR MEASURE FOR THIS PROBLEM.

VEHICLE/BARRIER IMPACTS AND CRASHWORTHINESS

Recently, several ongoing projects at LLNL have developed a focus on vehicle crashworthiness and interactions with roadside hardware. Work in this area has already resulted in numerous new code features and methodologies for this type of analysis, as summarized in recent works on vehicle/barrier interactions (Logan, 1992) and design for crashworthiness (Logan, Burger et al., 1993). One of the more novel features recently implemented into a test version of the NIKE3D code has been a steering and tire force interaction algorithm. The nomenclature and operation of this algorithm are described in Fig. 8. The feature is first being implemented into the implicit NIKE3D code to examine convergence and stability issues, but will be equally useful in DYNA3D as well. Essentially, user-defined nodes on the vehicle and tire are used to set up coordinate systems that combine with vehicle trajectory to define the slip angle between (V) and (**R**) as shown in Fig. 8. This slip angle is then used with the tire normal load and a very simple tire model to define the generated lateral load acting in direction (L). The steering angle between the vehicle and each wheel (4-wheel steer if desired) can be defined with load curve input to conduct vehicle handling maneuvers as shown.

One application of the vehicle steering feature in an impact analysis has been in a demonstration problem involving a recent patented barrier design due to A. McKay. The performance of this barrier when impacted by a large domestic sedan has been documented (Mak and Menges, 1992). We conducted a very coarse mesh simulation of this event in order to explore the robustness of our contact algorithms as well as the new steering algorithm. Fig. 9 shows the resulting simulation in which the vehicle impacts the barrier at a speed of 26.8 m/sec, with an angle of incidence of 26.2 degrees. The measured and calculated exit velocities were 18 m/sec. Lateral movement of the pinned barrier links also approximates that observed in the actual tests. We are continuing to develop more robust algorithms for handling such problems with both NIKE3D and DYNA3D. Currently, the preliminary implementation of the tire model in NIKE3D is such that the tire lateral force is proportional in magnitude and orthogonal in direction to the tire normal force. This does not allow for traditional chassis tuning methods to be explored. However, it provides an adequate development test for ensuring robustness of the implicit scheme used to achieve code convergence on each time step. We plan to add more realistic tire models as described elsewhere (Dirks, 1992).

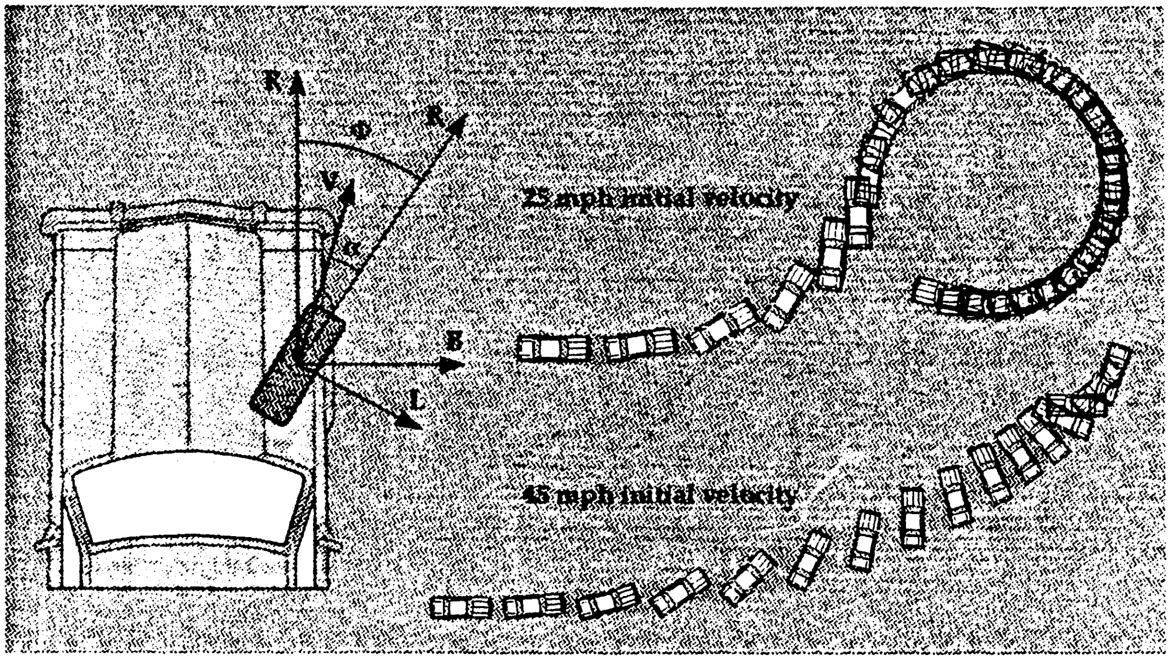


FIG. 8. VEHICLE STEERING ALGORITHM BEING IMPLEMENTED INTO NIKE3D USES VEHICLE COORDINATE SYSTEM (R-B), TIRE COORDINATE SYSTEM (R-L), TRAJECTORY (V), AND RESULTING ANGLES TO GENERATE LATERAL TIRE LOADS ALLOWING VEHICLE STEER DUE TO EACH TIRE USING LOAD-CURVE INPUT.

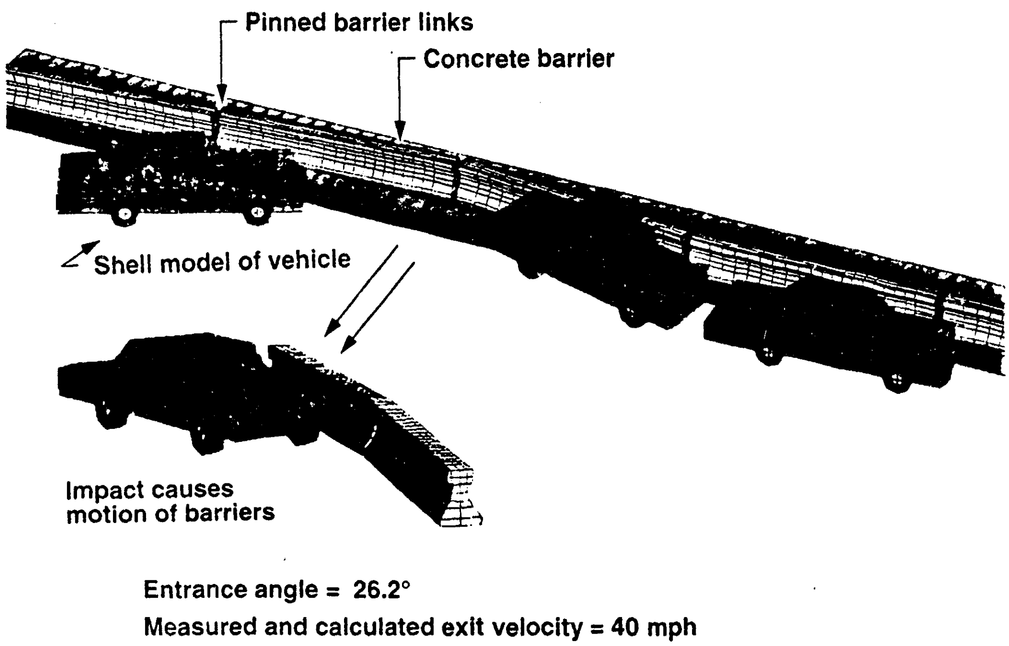


FIG. 9. MODEL OF A LARGE DOMESTIC SEDAN WITH VEHICLE STEER IMPACTING AN APPROXIMATION OF THE MCKAY/MGS BARRIER SYSTEM. PROBLEM IS A ROBUST TEST FOR THE STEERING AND CONTACT ALGORITHMS.

SUMMARY AND FUTURE WORK

The technology for analysis of crash and impact problems at LLNL continues to evolve and be incorporated into our NIKE and DYNA finite-element codes due to the needs of numerous programs involving LLNL and cooperative work. There are near one-to-one correspondences between the impact behavior of shell structures for submarine hulls and automobile stampings, between aluminum spaceframe shipping containers and vehicle chassis designs, and between the crush of composite penetrating weapons and lightweight vehicle rails in crush. Thus, the numerical technology for the analysis of these sets of problems evolves in a concurrent and leveraged manner. We are continuing our work both internally at LLNL and with the government and industrial community in these areas. Our most rapidly growing application is in passenger transport by auto, air, or rail. Crashworthiness of the vehicle structure is being explored by analysis of energy absorption and by coupling to occupant safety codes and criteria.

ACKNOWLEDGMENTS

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REFERENCES

Dirks, D.D., "3-Dimensional Computer Model for Vehicle Handling Analysis", M.S. Thesis, Univ. California, Davis, CA (1992).

Engelmann, B.E., "NIKE2D, A Nonlinear, Implicit, Two-Dimensional Finite Element Code for Solid Mechanics - User's Manual", University of California, Lawrence Livermore National Laboratory, UCRL-MA-105413, (1991).

Groves, S.E., Sanchez, R, and Feng, W.W.,"Multiaxial Failure Characterization of Composites," Composites: Design, Manufacture, and Application, edited by S.W. Tsai and G.S. Springer, proceedings of the 8th International Conference of Composite Materials, July 1991, published by SAMPE (1991).

Kay, G.J., "Impact Analysis of the UC-609 Shipping Package", Applied Mechanics Group, Mechanical Engineering Department, University of California, Lawrence Livermore National Laboratory, UCRL-JC-115372 (1993).

Keeler, S.P., "Understanding Sheet Metal Formability", Parts IV and VI, *Machinery Magazine*, May and July (1968).

Logan, R.W. and Lovejoy, S.C., "DYNA3D Analysis of the DT-20 Shipping Container", University of California, Lawrence Livermore National Laboratory, UCRL-ID-107884 (1991).

Logan, R.W., "Tire, Accident, Handling, and Roadway Safety," *Engineering Research and Development Thrust Area Report FY92*,, ed. S.Y. Lu, University of California, Lawrence Livermore National Laboratory, UCRL-53868-92 (1992).

Logan, R.W., "Implementation of a Pressure and Rate Dependent Forming-Limit Diagram Model Into NIKE and DYNA", University of California, Lawrence Livermore National Laboratory, UCRL-ID-105760 (1993).

Logan, R.W., Burger, M.J., McMichael, L.D., and Parkinson, R.D., "Crashworthiness Analysis Using Advanced Material Models in DYNA3D", paper presented at ASME Winter Annual Meeting, Symposium on Crashworthiness and Occupant Protection (1993).

Mak, K.K., and Menges, W.L., "Crash Testing and Evaluation of the MGS Barrier System", Texas Transp. Institute, The Texas A&M University System, College Station, TX (1992).

Maker, B.N., "NIKE3D, A Nonlinear, Implicit, Three-Dimensional Finite Element Code for Solid and Structural Mechanics - User's Manual", University of California, Lawrence Livermore National Laboratory, UCRL-MA-105268, (1991).

McMichael, L.D., "Evaluation of a Space Frame Impact Cage for Weapon Transport," University of California, Lawrence Livermore National Laboratory, UCRL-ID-113094, (1993).

Whirley, R.G., "DYNA3D, A Nonlinear, Explicit, Three-Dimensional Finite Element Code for Solid and Structural Mechanics - User's Manual", University of California, Lawrence Livermore National Laboratory, UCRL-MA-107254, (1991).

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