

Automobile Impact Forces on Concrete Walls

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SUMMARY

Current design procedures were reviewed and a few candidate analytical models for impact force predictions were evaluated. The one-dimensional vehicle model finally selected for subsequent calculations consists of a distributed mass representation of a car with variable strength and mass properties along its length. The engine, however, was considered to be rigid.

The vehicle data base for this investigation consisted of detailed strength and mass distribution information, as well as test data from low-speed, head-on impact with flat concrete barriers, for nine cars ranging from full-size to minicars. Test data were utilized to validate the analytical vehicle model.

The one-dimensional model was used to calculate impact force-histories on rigid walls due to head-on impact of each of the nine vehicles considered over an impact speed of 20 - 60 meters/sec. The sensitivity of computed forces to variations in mass and strength distributions was determined.

A three-dimensional lumped-mass vehicle model was used to predict the effect of various impact orientations on the force-histories for variation of impact angle in one plane. A lumped-mass structural model was then employed for a typical panel to determine the effect on structural response of impact orientation using the rigid-wall, force-time histories generated by the three-dimensional vehicle model.

To assess the significance of vehicle/structure interaction on the head-on impact force-histories, the simple lumped-mass model of a reinforced concrete wall panel was coupled to the one-dimensional vehicle model for numerous panel design configurations within the range of practical interest. Vehicle-structure interaction was found to have relatively little effect on the force-histories.

1. Introduction

The structural design of nuclear power plants in recent years has increasingly been concerned with the threat of main structure penetration or damage caused by a variety of high speed missiles. Sources for such threats range from high-speed fragments from internal equipment, impacting aircraft and tornado-borne debris. The last category is generally taken to include such miscellaneous wreckage as pipes and timbers but must also include air-borne motor vehicles as a credible possibility. Although a substantial number of studies have been reported dealing with various aspects of structural response and damage criteria for missiles, these studies have dealt either with the "hard" missile (i.e., relatively small, stiff penetrators) or with the very large, "soft" missiles such as aircraft. Little information is available which specifically deals with motor vehicle impact on nuclear facilities. Further, the automobile, considered as a missile, is intermediate in mass and size between the hard penetrators and the large missiles such as aircraft, and is likely to involve force levels and damage mechanisms which do not fall within the range of effects included in either of these extremes.

The procedure currently acceptable to the Nuclear Regulatory Commission (NRC) for considering automobile impact loads on Category I structures in nuclear power plants, consists of treating the automobile as a rigid missile which imparts its total momentum instantly to the structure. At low impact velocities the adequacy of this simplistic approach is of little concern because other loadings govern the design of exterior walls of Category I structures. However, recent studies suggest that relatively high impact velocities are likely to be attained by an automobile in a tornado in some geographical areas. At these velocities, automobile impact loads could very well dictate certain aspects of structural design; e.g., the size and configuration of reinforcing bars in reinforced concrete walls. It is therefore desirable to obtain a more accurate definition of automobile impact loads.

The objective of the investigation reported herein was to develop representative design-oriented loading data for reinforced concrete wall panels subjected to automobile impact considering the deformability of both the vehicle and structure. The study was solely analytical in nature and drew largely on the extensive body of low-speed automotive crash data and simulation techniques available from prior vehicle crashworthiness studies as a source of loading information.

2. Investigations Performed

The following topics outline the basic approach used to develop the resultant design-orientated data in the form of loading functions.

2.1 Data Collection

Data on automobile performance were collected for the conduct of the analysis in this investigation. Descriptive data representative of the spectrum of passenger vehicles were collected. This included mass and crushability characteristics. In addition, crash test results for the impact of passenger vehicles into heavy reinforced concrete walls [1, 2, 3] were compiled for validation of the analytical models. Reference [1] provides direct force-measurements as well as acceleration data. Typical results are shown in Figure 1.

2.2 Vehicle Model Selection and Evaluation

A literature review was conducted for crash models to calculate impact forces. The vehicle deformation models used to date for application to vehicle impact with nuclear power plant structures have been confined to one-dimensional head-on orientation models [4, 5, 6]. For purposes of this study, the baseline configuration was defined as head-on impact of an automobile into a rigid wall.

Comparisons with data from low-speed impact tests were made for linear spring models (LINEAR), distributed mass models (CONTMASS), and multiple mass models (COMPAT). Typical results are shown in Figure 1. During impact of a vehicle with a wall, there are two major interaction mechanisms which determine loading on the wall: (1) momentum transfer and (2) crushing or alternately, mass and strength effects respectively. Distributed mass models such as CONTMASS contain both mechanisms explicitly. Multimass models such as COMPAT also accommodate both mechanisms providing the springs connecting the masses have sufficient stiffness or strength near the limit of their stroke to allow "bottoming out" without overlap of masses. Single mass-spring models such as LINEAR or NONLINEAR can impart load to the wall only by crushing or deformation of the spring.

At low-speed impact the momentum transfer is relatively small and the crushing mechanism dominates generation of impact forces. At high-speed impact the reverse is true. This suggests that at low-speed all four types of models can adequately represent the impact conditions, but that at high-speed, the single mass-spring models are not suitable.

At high-speed impact, typically, a proper impact force signature should contain a significant "spike" due to impact for the relatively stiff engine with the wall.

The LINEAR model is not capable of predicting the engine spike and it usually gives a load duration which is much too long or a load magnitude which is too high depending on the assumed value for the constant spring stiffness in the model. Similarly, the NONLINEAR model does not exhibit the engine spike and has the tendency to either provide a load duration or magnitude which is too high.

A multimass model such as COMPAT is subject to overlapping of masses unless the spring properties are substantially stiffened at spring deflections approaching the maximum compression limit. When these stiffened springs are used, spikes in the force signature occur as a spring tends to "bottom out." The character and magnitude of these spikes will depend not only upon the intensity with which two masses tend to approach each other, but also upon the assumed bottoming characteristics of the stiffened spring interconnecting the two masses. This is especially important for spring bottoming corresponding to engine mass impact with the wall because a large spike in the force signature is normally produced and the properties of this spike become extremely sensitive to the assumed bottoming character of the spring(s) attached to the front of the engine mass. Another problem associated with the COMPAT model for high-speed impact is that the body mass of the vehicle (essentially most of the vehicle mass behind the firewall) is lumped into single mass. Consequently, at high-speed the model predicts an unrealistic force spike due to body mass impact with the wall. This phenomenon is not inherent with multimass models in general but occurs with COMPAT because of the limited number of masses available with which to model the vehicle. The body mass could be represented by

several masses instead of one. Another disadvantage of multimass models is that they are relatively expensive computationally.

A distributed mass model such as CONTMASS also does not accurately predict the engine spike if the engine mass is assumed distributed over the actual length of the engine and the crushing strength of the vehicle in the vicinity of the engine is set equal to that of the structural components attached to the fore and aft of the engine. If the actual crushing strength of an engine is used and the engine mass is distributed over the actual engine length, the model predicts an extremely large force spike which is probably realistic. However, the numerical integration time step necessary to produce accurate results in this situation is extremely small thus making the solution process very expensive.

As a result of the model evaluation, the model finally selected as the head-on vehicle impact model for use in this investigation is the Distributed Mass Model with the engine treated as a noncrushable mass and the remainder of the vehicle as a continuous crushable mass.

2.3 Effect of Structural Deformation

The vehicle model was coupled with an elastic, plastic one-degree-of-freedom flexural model for the structural wall panels. This simple representation of the wall panels was introduced to approximately determine the effect of structural deformation on impact forces.

The impact of one automobile into a wide variety of walls representing the practical range of structural design parameters was simulated. Calculations were made for impact speeds of 20, 40 and 60 meters/sec. Impact force functions were compared to the corresponding ones for impact of the vehicle with a rigid wall. Results showed that structural deformation has little effect on impact forces, as shown in Figure 2.

2.4 Effect of Impact Orientation

The relative severity of impact for frontal, rear, side and any oblique angle impact between these orientations was examined. This was accomplished with the use of a three-dimensional vehicle model. The walls were assumed to be rigid for the purpose of this part of the study. Rotational as well as translational velocity at impact was considered.

A translational velocity of 40 meters/sec in combination with zero and one revolution/sec angular velocity was used. The frontal impact crushing strength properties of the three-dimensional vehicle model were taken to be approximately equal to those of the one-dimensional frontal impact model and the side and rear crushing strength properties per unit area were assumed equal to those of the front. One full-size passenger vehicle was used in the calculation. It was found that the side-impact orientation produced the greatest peak impact force by about a factor of two over the frontal impact force as shown in Figure 3. Furthermore, the rotational velocity of one revolution/sec at impact was found not to significantly alter the impact force function and the three-dimensional and one-dimensional vehicle models produced comparable force functions for both side and frontal impact conditions even through the impact envelope, or "springs" of the three-dimensional model are massless whereas those of the one-dimensional model are not.

3. References

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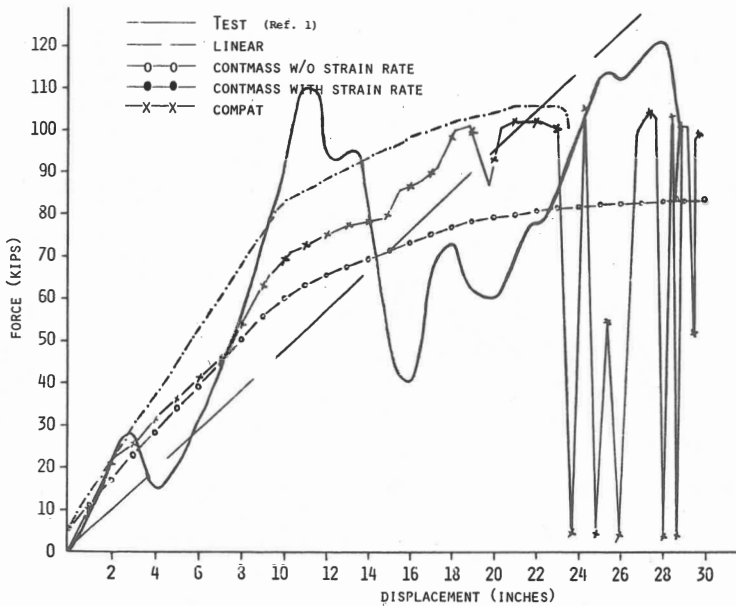


Figure 1 1973 FORD TORINO, 30 MPH IMPACT

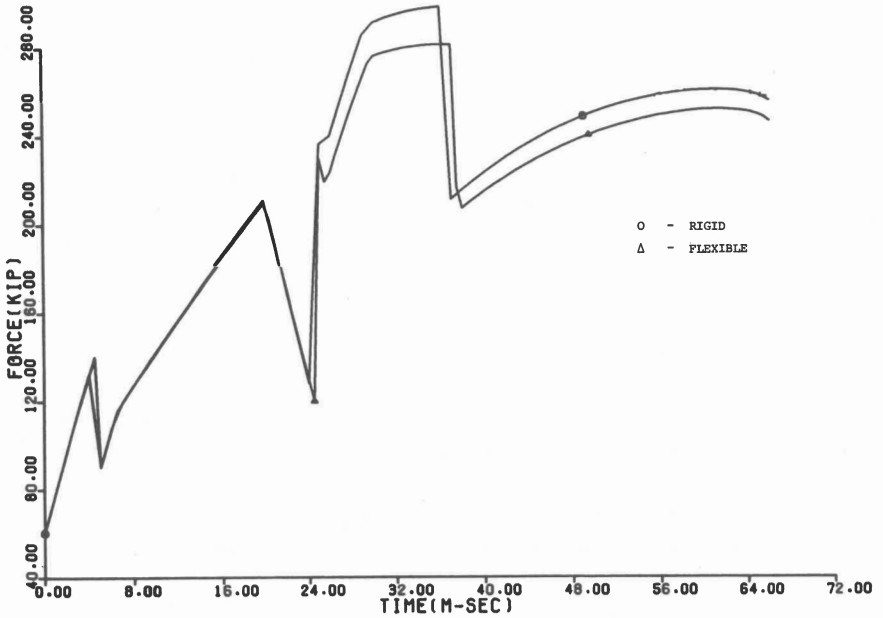


Figure 2 EFFECT OF WALL FLEXIBILITY ON IMPACT FORCE
FOR 12" THICK, 24' SPAN WALL AT 40 M/SEC IMPACT SPEED

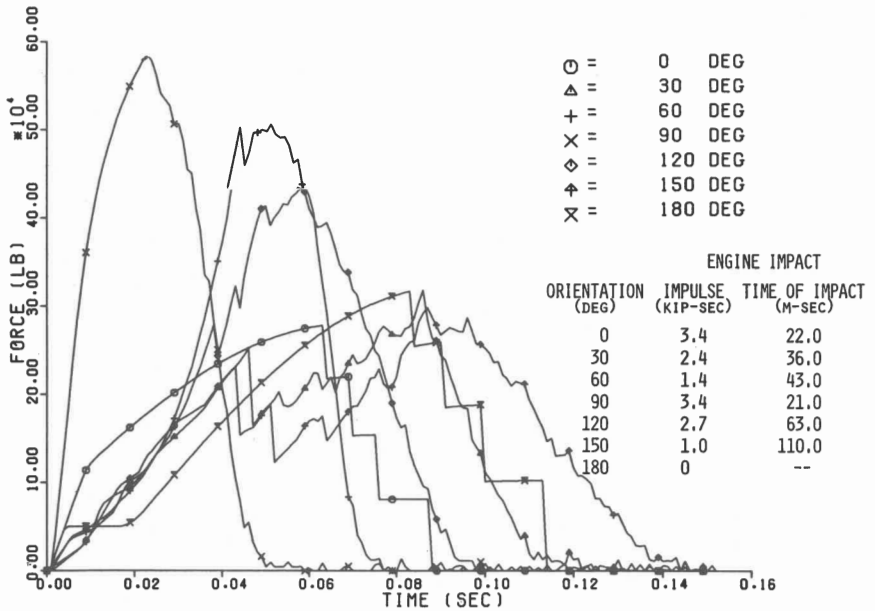


Figure 3 EFFECT OF VEHICLE YAW ORIENTATION OF IMPACT FORCE
-- PLYMOUTH SATELLITE, 40 METERS/SEC IMPACT SPEED