THE DYNAMIC RESPONSE OF SINGLE HEXAGONAL LMFBR CORE SUBASSEMBLY WRAPPERS

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SUMMARY

To analyze the dynamic structural response of the LMFBR core subassembly hexagonal wrappers to postulated local energy releases and the sensitivity of the response to variations in both the pressure loading and the material properties of the stainless steel, a finite-element computer code STRAW has been developed. Supplementing the analysis, out-of-pile experiments have been performed on single hexcan sections subjected to internal pressure pulse loadings. The tests have been designed with the purpose of validating, and where necessary, extending the scope of the code. The dynamic pressure loading was generated by an explosive source. The source was designed to produce conditions simulating those of a hypothetical core accident. An example chosen was the hypothesized pressure pulse created by a fuel-coolant interaction resulting from the failure of a misloaded, overenriched fuel pin.

A series of experiments was performed to study the effects of variations in material properties. The amount of coldworking to which the Type 316 stainless steel is subjected has a strong influence upon the ductility and the elastic yield point. The usual fabrication process produced a nominally 20% coldworking with a yield point of about 680 MPa. By designing a special set of dies for the drawing process, a very low ductility hexcan was produced for which the yield point was raised to 820 MPa. Conversely, the yield point was lowered to 170 MPa by a solution annealing process producing a highly ductile test hexcan. A metallurgical study was conducted to find a representative brittle simulant material for the irradiated end-of-life steel properties. An aging treatment for Type 446 stainless steel was developed which reproduced the expected tensile-flow behavior of the in-pile subassembly. Further study is underway to investigate the fracture properties of the simulant material.

The pressure pulses were generated by the controlled expansion of high-pressure detonation products from low-density explosives detonated inside a vented steel cannister. The orifice configuration of the cannister and the charge mixture ratio were designed to produce two specified pulse shapes. A charge containing 37.7 g PETN mixed with 35 wt % inert, hollow-glass microballoons developed a pressure pulse peak of 9.5 MPa at 1.0 ms. Increasing the PETN to 41 g resulted in a 14.6 MPa peak pressure, and increasing the explosive concentration to 90 wt % in the mixture increased the burning rate and the pulse risetime, so that the peak occurred at 0.6 ms. The code computations showed that the hexcan response is relatively more sensitive to the pulse risetime than to variations in the peak magnitude.

The material properties were found to have a strong influence upon the hexcan response. Under the 9.5 MPa pulse, the annealed hexcan deflected 0.73 cm, compared to only 0.09 cm for the 50% coldworked material. Close correlations with the experimental results were achieved by inclusion of the strain-rate effects. These effects were measured in separate tensile tests. The good comparisons establish the capability of the code to predict the dynamic response of a single hexcan under axially uniform pressure loadings. The sensitivity of the response to the pressure pulse and material properties has been demonstrated.

1. Introduction

The possibility of an accidental failure, say of a fuel pin cladding, in one subassembly giving rise to further failures within the core through the propagation of disturbances to other subassemblies presents a consideration for the safety analysis of the Liquid Metal Fast Breeder Reactor. A subassembly wall failure could be caused by a high local thermal load or a severe local pressure pulse. The damage could conceivably be propagated by means of a number of mechanisms that have been hypothesized. Any assessment of the possible spread of damage must be based upon an understanding of the capability of the structural elements of the core to impede the transmission of failures from subassembly to subassembly. Attention is concentrated here upon the effects of purely mechanical loadings. The thermal effects, which give rise to thermal stresses and possible melting are not treated. Restricting attention to the mechanical phenomena, the analysis of a possible accident sequence must include consideration of (a) a definition of local subassembly accidents capable of generating sufficiently substantial pressure pulses to cause significant material damage, (b) definition of the material properties of the core structure throughout its operating life and during the possible accident conditions, (c) description of propagation phenomena and possible fracture modes and specification of locations, and (d) specification of the subassembly structural geometry and changes in that geometry, including the surrounding subassemblies, the coolant, and any auxiliary structural elements such as control rod guide-tubes which may be affected by pressure propagations. An additional consideration is that the deformation resistance of the subassembly walls to external pressure loads may be significantly influenced by the subassembly internals, which include the fuel pin and wire wrap spacer configuration.

In the event of an accidental pressure release within a reactor core subassembly, the hexagonal subassembly wrapper may become permanently deformed. Removal of the damaged subassembly from the core depends upon the extent of the damage both to the accident subassembly and also to the surrounding subassemblies. Permanent deformations may also interfere with control rod motions. To predict the deformations and strains which a hexcan wrapper may undergo when subjected to such accidental pressure loads, a computer code STRAW [1] has been developed at Argonne National Laboratory. To verify the capability of the code to model the hexcan response under the accident conditions, well-defined simple experiments were performed in which the test hexcan response to known loads was measured. The basic objectives of the experiments were (1) to measure the deformations and strains in hexcans subjected to uniformly distributed internal pressure pulses, (2) to compare the measurements to code predictions, and (3) to assess the accuracy of the comparisons and determine the sensitivity of the response to variations in the loading and material properties. These dynamic tests constitute a continuation of an experimental program in which a first phase consisted of preliminary tests on the response of hexcans to hydrostatic pressure loads. The final phase of the program will include experimental tests on the response of a cluster of hexcans submerged in a simulated coolant liquid. The cluster tests will represent an "accident subassembly" surrounded by six adjacent subassemblies. A pressure pulse will be generated within the central hexcan representing the accident subassembly. The expansion of this internally loaded subassembly will exert external pressures upon the surrounding hexcans and will provide the simulated conditions for subassembly-to-subassembly damage propagation.

Because of the wide range of initiating conditions which may be postulated, the definition of a representative pressure pulse to be used in the experiments presents some difficulty. One of the more likely initiating events which may occur during the lifetime of a reactor is the failure of the cladding of one or more fuel pins near the end-of-life conditions. This failure may lead to the release of high pressure fission gas producing the pressure pulse which is to be simulated in the experiments. Other events such as a meltdown resulting from a subassembly blockage and causing thermal interaction between the coolant and hot fuel or cladding, or an overpower transient producing fuel vaporization, can be reduced to a very low probability by proper reactor design and control. The pressure pulse employed in the present test program is based upon a calculation representing the meltdown of several overenriched and misloaded fuel pins, and the subsequent thermal interaction with the coolant. Based upon these conditions, the resulting calculated pressure pulse rose to a peak of 10 MPa with a 1-msec risetime and a total pulse width of about 10 msec. A ported cannister design containing a PETN low-density, low-pressure charge mixture was developed at Stanford Research Institute [2] to reproduce this specified pressure pulse.

The primary purpose of the test program is to verify, modify, or extend the capability of the computer code to predict subassembly damage propagation, rather than to simulate the worst possible accident. Consequently, no attempt was made to generate a representative upper bound for the pressure source because the complexity of the resulting severe damage would introduce ambiguities in the interpretation of the data for code verification. The point of view adopted here is that examination of the end results of a large explosion with extensive damage will give qualitative failure information but will not reveal a detailed time history of events.

2. The Mechanical Properties of the Steel

The mechanical response of the hexcan to pressure loads is strongly dependent upon the mechanical properties of the steel. The yield stress for the Type 316 stainless steel can vary over a wide range, depending upon the ambient conditions, and upon the history of the metallurgical and forming processes that the steel undergoes. Tensile specimens were cut from the test hexcans and the stress-strain properties for each material were determined by standard tensile test methods. Under actual reactor operating conditions the tensile properties change with variations in temperature and exposure to irradiation. The hexcan tests were performed at room temperature with unirradiated ducts. However, it is desirable to perform tests for hexcans with varying material properties, both to check the capability of the code to compute the effects of variations in the material properties, and to determine the sensitivity of the hexcan response to changes in material properties. The steel can be hardened and made less ductile by mechanical cold working. A 50% coldworking will increase the yield point stress by a factor of about 4.25 over the yield point for the annealed steel. The strain at which the ultimate point occurs is significantly reduced by the coldworking, from a value of 63% down to 5%, so that the 50% coldworked steel can be extended only about 1/12 the distance of the annealed steel before the ultimate point is reached.

The test hexcan deformations are measured at the midplane between the duct ends which are constrained against axial displacements, so that the deformations and strains are in the two-dimensional, plane-strain mode, with no components in the axial direction. Under these conditions, the hexcan wall can be modelled mathematically as a deflecting beam. The input stress-strain relationship to the computation must be modified by the plane-strain correction which effectively raises the measured uniaxial tensile test stress values. Also, under dynamic loading conditions, the material properties are influenced by strain-rate effects. For the pressure pulse peaking at 9.5 MPa with a 1 msec risetime, the peak strain rate at the midflat of the annealed test hexcan was computed to be 270 sec^{-1} and in the corner 1000 sec^{-1}. The effect of these high strain rates is to stiffen the material by effectively raising the yield point. A computational strain-rate model of the material effects was introduced into the code, in which the yield strength σ_y is a power function of the strain rate $\dot{\varepsilon}$

$$\sigma_y = \sigma_0 \left[1 + \left(\frac{\dot{\varepsilon}}{B} \right)^n \right] \tag{1}$$

The zero- strain-rate yield stress is σ_0, and B and n are constants derived from a fit with experimental data. The empirical constants B and n for mild steel are about 40.4 and 0.19. Trial computations have shown that the above yield stress relationship to strain rate is not sensitive to the values of the parameters and moderate variations will give approximately similar overall fits to the experimental data.

Since permanent deformation occurs in the hexcan experiments, questions are raised with regard to the effects of strain rates upon the plastic flow range of the stress-strain relationship. From an examination of the methods of measuring strain-rate effects, it is apparent that at present there are no reliable models describing plastic flow behavior characteristics under varying rates of strain. The model assumed for the computer code calculations is that the yield stress varies with the strain rate in accordance with the empirical power law eq. (1) given above, and that the plastic flow range of the stress-strain curve is simply rigidly translated up or down with the yield stress as the strain rate first increases and then decreases during the dynamic hexcan test. Data given by Oak Ridge National Laboratory [3] for an annealed Cr-Mo steel roughly substantiates this assumed behavior.

Tests performed by the Materials Science Division at Argonne National Laboratory determined the strain rate influence upon sample tensile specimen coupons cut from the test hexcan sections. The results shown in Fig. 1 indicate a gradual rise in the yield strength with increasing strain rate, but confidence in the stress values beyond a strain rate of 5 sec^{-1} is not sufficient to extend the relationship to higher strain rates. For the lower strain rates up to about 0.04 sec^{-1} the tests were made on an Instron tensile testing machine. For the first 5% strain the data were obtained from an extensometer attached to the center 1-inch length of the tensile specimen gage section; for the higher strains the conventional load versus crosshead displacement data were obtained. For the higher strain rates from 0.04 sec^{-1} to 144 sec^{-1} the tests were performed on an MTS (Materials Test System) electrohydraulic servo-controlled testing machine. On this machine, force was measured with a high-response quartz piezoelectric load washer. The piston displacement feedback signal came from a LVDT built into the linear actuator. For tests at strain rates of below 1.6 sec^{-1}, conventional extensometers were used for strain measurements. At the higher strain rates the load versus crosshead displacement signals were used for the yield stress determination.

3. Comparisons of Calculations with the Experiments

A series of hexcan sections of varying ductility were subjected to representative pressure pulses at room temperature. The pressure pulses shown in Fig. 2 were generated by pressure sources based upon the controlled expansion of high-pressure detonation products from low-density explosives detonated inside a vented steel canister. A mixture of 65% (by weight) PETN and 35% hollow glass microballoons produced the 9.5 MPa peak pressure pulses; the 14.6 MPa peak pressure was produced by a source mixture of 90% PETN and 10% hollow plastic microspheres. The pressures were measured with transducers, and the dynamic strains in the circumferential and axial directions were measured with foil strain gages. To measure the dynamic wall deflections a novel technique was employed using a light-emitting diode (LED). Light reflected from a mirror piston mounted on the wall is transmitted through a fiber-optic bundle to a phototransistor. The electrical output is a function of the light intensity which varies as the hexcan deforms, and after calibrating, gives a measurement of the wall movements. Comparisons of the test data with STRAW-code calculations demonstrated that the internally pressurized hexcan response was sensitive to the material properties of the steel, and that the material description should include the strain-rate effects. Further computations indicated that the deformation response is appreciably influenced by the initial shape of the pressure pulse. Particularly significant is the initial slope of the pressure-time curve and also the point at which the slope begins to diminish from the essentially linear initial rise. Under some conditions the values of the slope and the extent of the linear rise can have a more important influence upon the hexcan response than the magnitude of the pressure peak.

To demonstrate that the hexcan response depends strongly upon the initial pressure rise and can be relatively insensitive to the peak pressure magnitude, comparisons were made with the response computed for a hypothetical pressure pulse coinciding with the initial rise of the 9.5-MPa experimental pulse, but with the peak pressure raised to 14 MPa at 1.6 ms. The computed midflat response in Fig. 3 shows that the maximum deflection (0.736 cm) for the annealed hexcan is not increased, as might be expected, by the increased pressure. We see in Fig. 3(b) that the response is unchanged throughout the first 1.0 ms; a slight outward deflection then occurs because of the increasing pressure.

Another sensitivity computation was made for a second hypothetical pressure pulse, again with the same initial slope, but the linear portion was extended to 9 MPa rather than the original 8 MPa before curving off to a peak of 12.5 MPa. The increase of the linear rise caused the midflat deflection to increase from 0.736 to 0.825 cm.

The computed response of the 50% coldworked hexcan to the experimental 9.5-MPa pressure pulse is shown in Fig. 4(a). The sensitivity of the midflat response to doubling the slope is shown in Fig. 4(b). Although the pressure peak has been held fixed, the hexcan response has significantly changed. The peak midflat displacement has increased from 0.099 to 0.125 cm, and a very pronounced vibratory mode has been induced in the hexcan wall motion.

For the annealed steel, the strain-rate effect upon the material properties strongly influences the hexcan response. Using the strain-rate effects for mild steel (curve (d) in Fig. 1), the computed response shown in Fig. 5 correlates well with the experiments.

For the 50% coldworked steel, the parameters for mild steel, curve (a) in Fig. 1, do not fit the stress-strain data as well as the parameters for curves (b) and (c). The considerable sensitivity of the computed hexcan response to the assumed strain-rate effects is shown in Fig. 6. The experimental data fall between the strain-rate effects curves (b) and (c). The conventional mild-steel relationship results in a steel that is much too stiff, whereas if the strain-rate effects are ignored, the steel is not stiff enough. The midflat deflections are compared in Fig. 7. The test deflections appear to be somewhat greater than the computed values corresponding to curve (c), whereas the strain values in Fig. 6 are somewhat less. The apparent explanation is that the deflection measurements made with the LED displacement gage are not as accurate as the strain-gage measurements.

For the relatively high pressure peak of 14.5 MPa, a considerable region of the hexcan is strained beyond the elastic limit, so that the influence of the strain rate upon the yield point has an important effect upon the permanent deformation. For a lower pressure loading with a peak of 9.5 MPa, the computations indicate that the strain rate has a negligible influence upon the deformation. The computed strains at the midflat are compared with the experimental strains in Fig. 8.

4. Comments and Conclusions

An experimental program has been undertaken to determine the response of LMFBR-type subassemblies to local subassembly accidents. The objective is to perform well-defined experiments in which pressures, deflections, and strains can be measured. Care was taken to determine material properties of the hexcans and to ensure that the properties were uniform throughout a specimen. Results from the tests are compared with computer-code calculations to check the validity of the analysis and where necessary to modify models for more meaningful correlations. The validated codes may then be used to calculate the response of subassembly ducts under in-reactor accident conditions.

The comparisons show good agreement between calculations and experimental results for annealed, 20 and 50 percent coldworked Type 316 stainless steel ducts. These tests and comparisons show the way in which hexcans distort under internal and external pressures. The tests can be used to extrapolate directly to cases in which the risetime of the pressure pulse is significantly longer than the natural period (about 0.3 sec) of the hexcan.

A pressure source has been developed which duplicates the general characteristics of a local accident, together with the development of a basic theory which can be applied to the design of other pressure sources. It has been demonstrated that 1 ft-long hexcans are adequate for single, out-of-pile hexcan tests. Material properties for annealed and coldworked Type 136 stainless steels have been determined, and diamond-point hardness tests have demonstrated that the material properties were uniform both around the circumference of the hexcan and through the wall thickness.

Future work will be concerned with testing ducts with material properties more closely approximating those of end-of-life ducts. Although these materials will have low ductility and a yield and ultimate strength approximating end-of-life ducts, further effort will be required to define the strain-rate characteristics of the materials used in the tests. Propagation phenomena and the effect of intersubassembly coupling in damage propagation will also be investigated.

5. Acknowledgements

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[2] C. M. Romander and D. J. Cagliostro "Experiments on the Response of Hexagonal Subassembly Ducts to Internal Pressure Pulses" Proceedings 4th Int. Conf. on Structura Mechanics in Reactor Technology, San Francisco, California 15-19 August 1977, Paper E 3/0

[3] R. L. Klueh and R. E. Oakes, High-strain-rate tensile properties of annealed 2¼ Cr-1 Mo Steel, ORNL-TM-5028, October 1975.

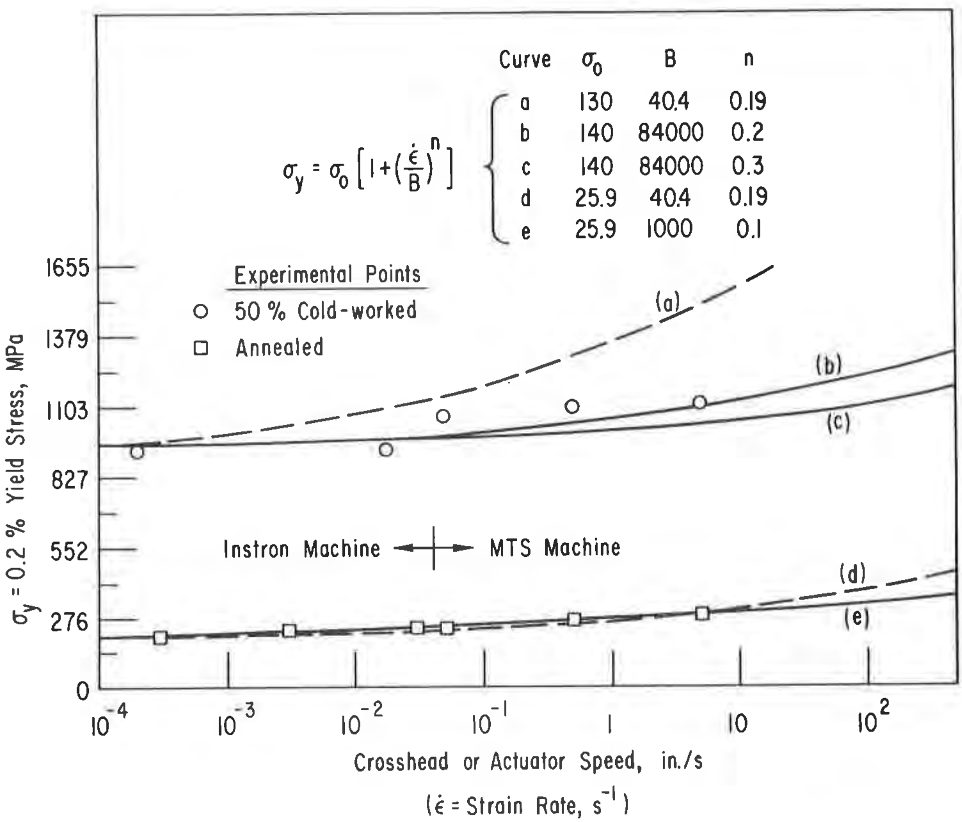

Fig. 1. Strain-rate Effect upon the 0.2% Offset Yield Point for Annealed and 50% Coldworked, Type 316 Stainless Steel, 1-in Tensile Specimen

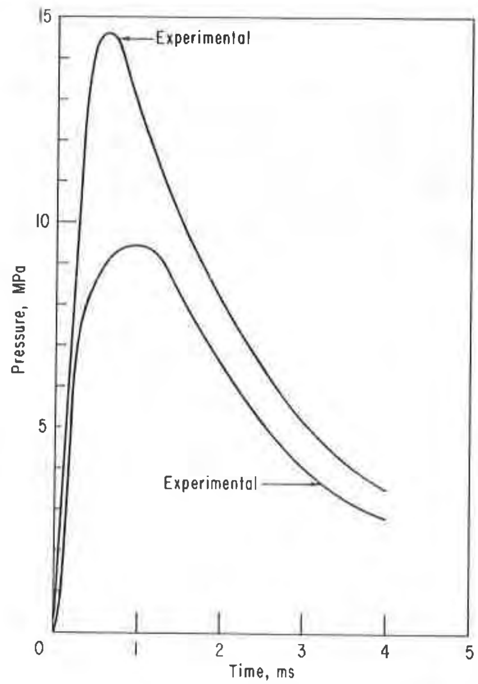

Fig. 2. Source Pressure Pulses for Internally Loaded Single Hexcan Tests

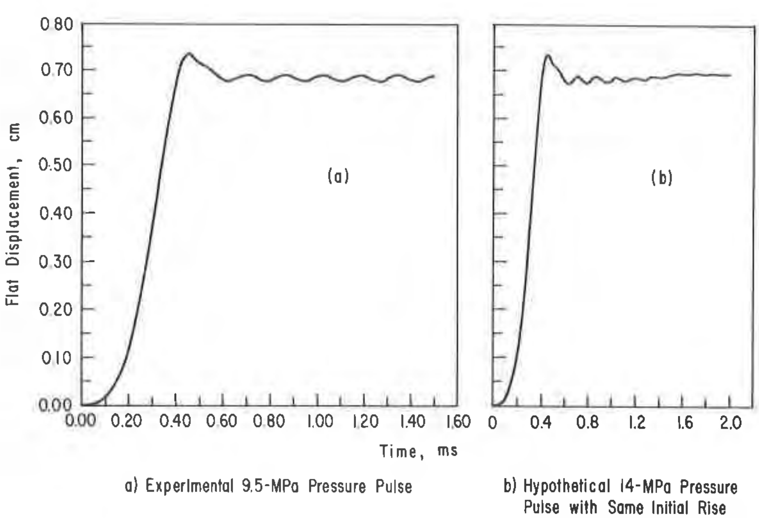

Fig. 3. Computed Effect of Increasing the Pressure-pulse Magnitude While Maintaining the Same Initial Pulse Shape for an Annealed Hexcan.

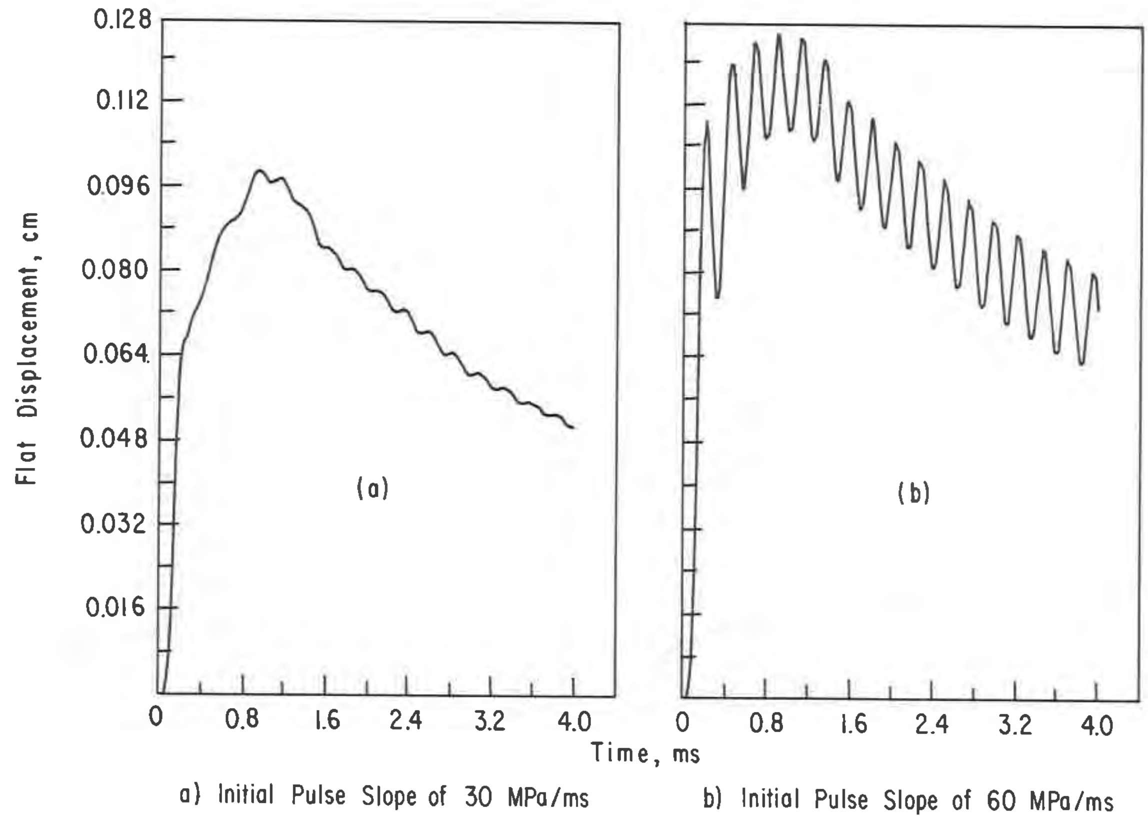

Fig. 4. Comparison of Midflat Response for 50% Coldworked Hexcans to Change in Initial Pressure Rise of Internal Pulse.

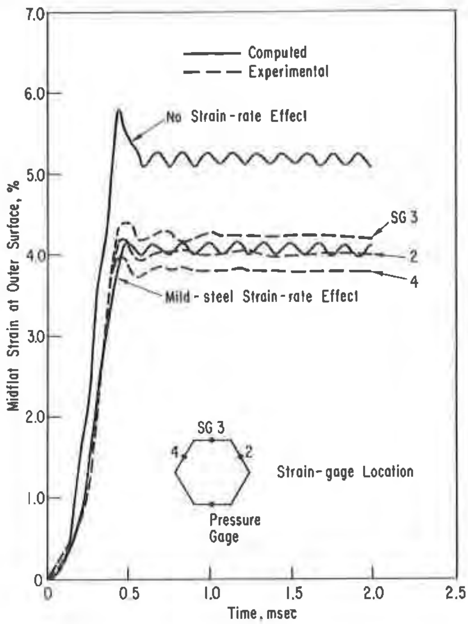

Fig. 5. Comparison of Computed and Experimental Midflat Strain for Annealed Type 316 Stainless Steel, 9.5-MPa Peak Pressure Pulse [Refer to Fig. 1 for definition of mild-steel strain-rate effect, curve (d)]

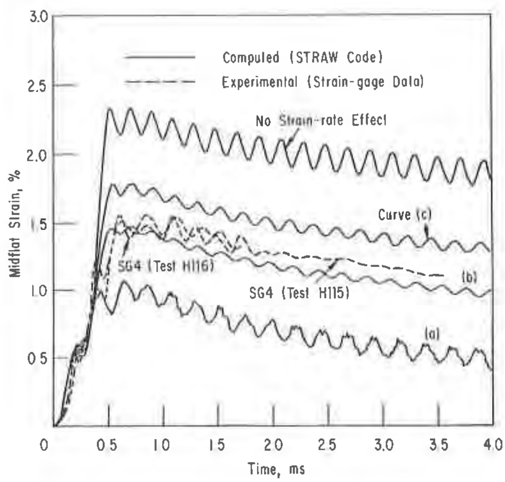

Fig. 6. Comparison of Computed and Experimental Midflat Strain for 50% Coldworked Type 316 Stainless Steel; High Pressure (14.5-MPa Peak). [Refer to Fig. 1 for definition of strain-rate parameters for curves (a), (b), and (c).]

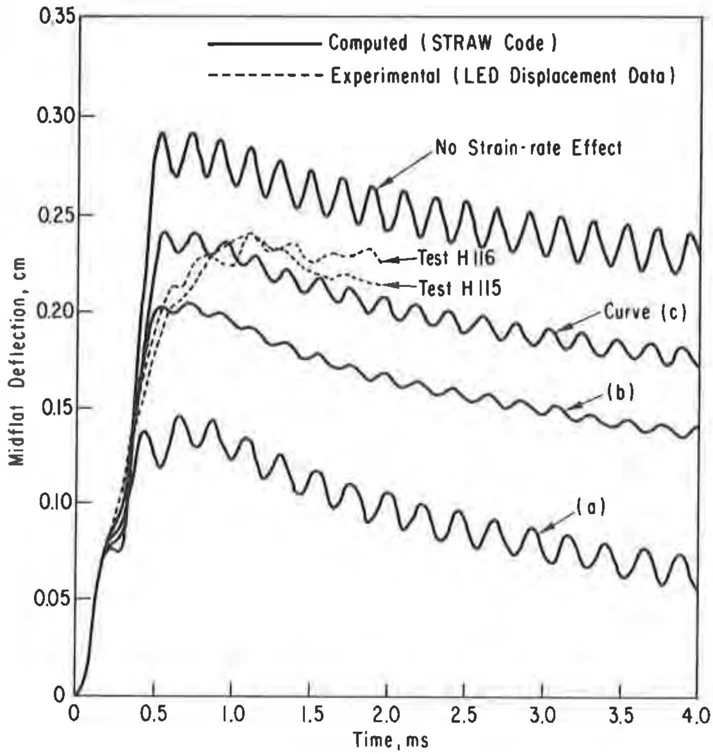

Fig. 7. Comparison of Computed and Experimental Midflat Deflections for 50% Coldworked Type 316 Stainless Steel; High Pressure (14.5-MPa Peak). [Refer to Fig. 1 for definition of strain-rate parameters for curves (a), (b), and (c).]

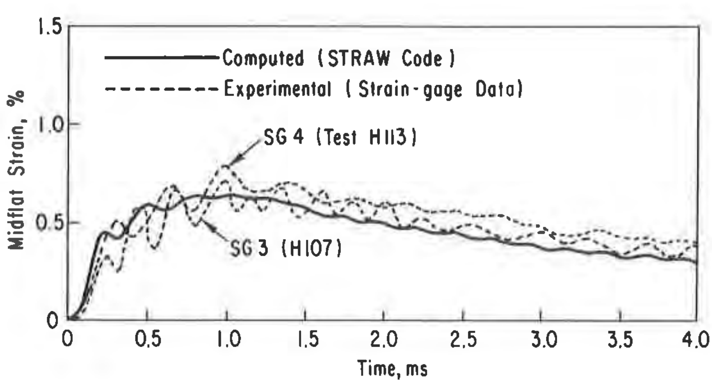

Fig. 8. Comparison of Computed and Experimental Midflat Strain for 50% Cold-worked Type 316 Stainless Steel; Low-pressure (9.5-MPa Peak) Internal Loading.