STRUCTURAL DYNAMICS STUDIES FOR SINGLE AND CLUSTERED SNR-300 FUEL ELEMENTS: A COMPARISON OF ANALYTICAL AND EXPERIMENTAL RESULTS

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SUMMARY

Structural damage may occur in liquid metal cooled fast breeder reactors (LMFBR) when local failures escalate to a fast release of excessive thermal energy within one fuel element. Time scales (5. to 50. msec) and peaks of associated pressure pulses (50. to 500. bar) may exceed the burst pressure of the hexagonal wrapper containing the pin-bundle. Though after fuel element rupture the pressure level in the vicinity is markedly reduced, still a significant pressure field is propagating through the core. Therefore surrounding subassemblies or control rods are exposed to impulsive differential pressures causing duct flexure as well as local cross section deformation.

A theoretical and experimental research program at GfK Karlsruhe investigates the mechanical effects of conservative pressure transients on LMFBR fuel elements. As part of the program this paper describes two computer codes (BEDYN-2, C0RE-1) for non-linear structural dynamics of single as well as clustered subassemblies. Important features and idealizations of mechanical models are discussed before the codes are applied to several loading cases. Then two types of subassembly deformation experiments are outlined, and original records of the pressure pulses are used as input for BEDYN-2 to predict and compare deformation histories with experimental findings:

(1) Quasistatic plane strain flat-to-flat loading of the hexagonal wrapper with and without the stiffening pin-bundle.

(2) Transverse impulsive loading of a complete 1 : 1 SNR-300 type fuel element model on roller supports.

In addition, pressure records from underwater explosion tests on SNR core models are taken as input for the multirow dynamics code C0RE-1 and fairly good correlations were found between measured and predicted permanent deformations.

The following results and conclusions can be summarized:

- Transversely loaded LMFBR type subassemblies show a strongly nonlinear load-deformation behavior for both dominating modes: Duct flexure and local cross section flattening.
- Understanding and modelling of the crushing behavior of the pin-bundle, particularly the plastic distortion of the spacer grids is essential for a realistic simulation of the flattening mode.
- Large geometry changes and strain-rate effected elastoplastic material behavior have to be accounted for since both significantly influence the permanent deformation of the structure and its capability to absorb energy.
- One-dimensional mass-spring models (code C0RE-1) are useful for the approximate dynamic elastoplastic analysis, provided that realistic information is available on the nonlinear structural behavior and dominating modes of deformation.
- A two-dimensional lumped parameter hinge model used in the code BEDYN-2 is suitable for the nonlinear analysis of both static and transient structural response. No additional input information is required on components behavior.

1. Introduction and Problem

Safety investigations for LMFBRs have to consider local failure situations in one fuel element which may escalate to a hypothetical CDA. A local failure is for instance a fuel-coolant-interaction (FCI) throughout one subassembly, which may cause a fast release of excessive thermal energy (conservative assessments yield 1. to 2. MWsec within 5. to 50. msec [1], [2], [3]), leading to a dynamic pressurization of the thin-walled hexagonal wrapper (50. to 500. bars in a fully constrained geometry [2], [5]), rupturing of this wrapper and impulsive loading at the surrounding fuel elements or control rods as shown in Fig. 1 (see [3], [4], [5], [6]). To rule out failure propagation it must be shown that these fuel elements adjacent to the incident element are able to withstand such loadings.

Therefore a combined theoretical and experimental research program has been performed at GfK Karlsruhe to investigate possible mechanical effects of given pressure transients on single and clustered fuel elements [8], [7], [4]. As part of the program this paper gives typical numerical results obtained from two structural dynamics codes (BEDYN-2, CØRE-1), which are utilized to predict the nonlinear dynamics of single as well as multiple fuel elements due to given pressure transients or acceleration loading [6], [9]. CØRE-1 is a multirow core dynamics code which was developed to analyze large scale explosion tests on SNR-300 core models and to predict the response of clustered elements with any given nonlinear force-deflection behavior under arbitrary time-dependent loading. The purpose of the more refined code BEDYN-2 is to analyze single subassemblies under very different static or dynamic loading and boundary conditions; here usual material properties (yield stress, hardening slope, rate-effects) are part of the general input and the code is for instance used to predict nonlinear force-deflection characteristics of any fuel element as input for CØRE-1. Single subassembly static and impulsive experiments were performed to verify and improve the theoretical models underlying primarily BEDYN-2. For this purpose the loading input is taken from these experiments [9] and then numerical response predictions are compared with experimental records. In addition pressure records from the underwater explosion tests on SNR-300 core models [5] are taken as input for CØRE-1 analyses, and the response predictions are compared with findings from the tests.

2. Theoretical Simulation and Subassembly Experiments

The outlined core deformation problem is schematically illustrated in Fig. 1 giving two simplified cross sections through the disturbed part of an LMFBR-core. Mainly two approaches have been persued in the past to investigate the coupled 3D fluid-structure-dynamics problem:

- Large scale experiments for specific reactor core configurations using tailored explosive charges to simulate specified pressure loadings [3], [5], [12].
- Extensive finite element simulation of the wrapper and coolant involving many degrees of freedom for one subassembly [13], [14], [15].

A compromise between both lines has been followed at Karlsruhe by developing computer codes such as BEDYN-2 (single subassembly dynamics [9]) and CØRE-1 (multirow core dynamics [6]), and at the same time performing single subassembly static and impulsive experiments

[9] in addition to large scale explosion tests on SNR-300 core models [5].

The outlined problem is idealized by the following assumptions:

- A rotationally symmetric transient pressure loading P_o, ΔP_i (i = number of subassembly row around incident element, Fig. 1).
- The external, transverse pressure loading ΔP_i has to be known in space and time (decoupling of fluid-structure problem).
- Relevant loading rates are sufficiently low and the thin-walled hexagonal wrapper tubes are slender beams so that wave propagation effects in the steel and both rotary inertia as well as shear deformation can be neglected.
- Elastoplastic beam theory is employed in conjunction with the principle of virtual work in order to formulate the equations of dynamic equilibrium. The concept of a generalized "elastoplastic hinge" is introduced [9], [10] and lumped masses are used to discretize the continous structure.

2.1 Response of Single Subassemblies

The structural response of a transversely loaded single fuel element is mainly affected by two interacting deformation modes: The beam-bending of the slender duct between two stationary supports 1 and 2 (Fig. 1), and the local distortion of the hexagonal cross-section due to ΔP_i. The cross section flattening compresses the pin-bundle inside the wrapper tube, so that crushing and frictional distortion of the spacer grids will generate high interaction stresses along the hexagonal interface.

BEDYN-2 uses lumped masses which discretize the subassembly inertia both in the axial (z-axis) and circumferential direction ($r\varphi$-plane, Fig. 1) of the fuel element. The mass points are connected by elastoplastic beam elements, and the deformation is concentrated at nodal hinges, which are located at the mass points. A general concept has been developed to describe the time-dependent state of the elastoplastic hinges, which may be visualized as "rotational springs" with nonlinear moment-rotation characteristics (lumped parameter hinge model [9]). The dynamic plastic material behavior is described by a bilinear stress-strain law with kinematic hardening and a strain-rate dependent flow stress according to [16]. Pin-bundle behavior is simulated by a homogeneous compressive material with a nonlinear hysteretic deformation characteristic.

To verify the outlined lumped parameter hinge model and to understand key phenomena of the subassembly response behavior mainly two groups of experiments were conducted on a drop-test facility [7], [9]:

- Static, displacement controlled plane strain flat-to-flat loading of the hexagonal wrapper with and without the stiffening pin-bundle.

- Impulsive transverse loading of a complete fuel element on roller supports (load control by drop-mass and -height in conjunction with properly sized crushing material between striking mass and fuel element model).

As an example Fig. 2 shows some results of the impulsive loading experiment DB 33 on an SNR-300-type fuel element model. Original time records are given of the impact force F, the reaction force F_s at the roller supports, the upper and lower subassembly flat displacement at L/2, the acceleration A of the transmitting ram above the model and finally the displacement of the heavy, spring suspended mounting table, which carries the model. In this particular experiment the drop mass of 399. kg attained a kinetic energy of 9790. Joule just prior to contacting the crushing material. The following energy partition was found from a detailed analysis of the experimental data using [17]:

Total energy transmitted to the subassembly by the force F(t)	:	4240. Joule
Energy absorbed by the crushing material	:	3924. Joule
Impact losses at transmitting parts	:	~900. Joule
Energy transmitted to the heavy table	:	726. Joule

The digitized force record F(t) is used as dynamic loading input for corresponding BEDYN-2 analyses. In case of static displacement controlled conditions the structural loading is unknown, and the code uses specified nodal accelerations as input. For the case of the dynamic test DB 33 Fig. 3 shows some typical results of a numerical response prediction which is directly comparable to Fig. 2:

Upper (s_3) and lower (s_1) fuel element flat displacement at L/2, the upper flat nodal acceleration $\ddot{s}_3$ versus time and the history of subassembly energy partition (W = total energy transmitted to the subassembly, W^{DB} = duct bending and W^{DA} = cross section flattening deformation energy, W^P = pin bundle deformation energy, W^K = kinetic energy of the system). The overall impulse of the measured input force F from Fig. 2 is 3390. (Nsec); first yielding was predicted to occur after 6.35 msec at the sideward hexcan corners at L/2. The following main quantities are used to compare experimental and theoretical results:

		Experimental Results	BEDYN-2 Prediction
Duct bending deformation at L/2 (mm)	peak	55.0	59.0
	permanent plastic	42.0	41.9
Cross section flattening under loading area (mm)	peak	~9.0	15.0
	permanent plastic	7.3	4.58

	Experimental Results	BEDYN-2 Prediction
Total energy transmitted to the subassembly by the external force (Joule)	4240.	3790.
Time where peak duct bending is attained (msec)	~40.	34.2
Time where peak cross section flattening is attained (msec)	~25.	14.9

The overall agreement of these most important response data is relatively good except for the cross section flattening; deviations of the latter (up to 40 %) are due to local plastic buckling and a very complex 3D strain distribution around the loading area (Fig. 2). In general it was found for 2D conditions that permanent hexagon deformations are predicted within about 10 % even when using only six corner nodes [9]. Similar BEDYN-2 results were found from predictions of static plane strain experiments. In all cases code input of static and dynamic wrapper material properties is extracted from several tension test series which were performed in collaboration with Euratom/Ispra.

2.2 Response of Clustered Subassemblies

The response of several clustered fuel elements is even more complex: Radial and sideward interaction of adjacent elements will occur in the $r\varphi$-plane of Fig. 1, and relative subassembly displacements will cause a squeeze-type flow of the coolant between the closely spaced elements (see companion paper [11]). Structural collision may occur under extreme loading conditions.

The multirow core dynamics code CORE-1 [11] is based on dynamically equivalent systems of point masses and nonlinear coupling springs (spoke-model). The squeeze type coolant flow between the elements is simulated by a coupled flow model [6], [11]. In contrast to BEDYN-2 this code requires input information on the global structural load-displacement behavior, which is taken either from static analyses with BEDYN-2 or from single subassembly experiments. As an example Fig. 4 shows a transient analysis of the underwater explosion test 3 on an SNR-300 core model [5]. Original pressure records from this test are used as loading input for CORE-1 and elastoplastic load-displacement behavior is taken from static subassembly experiments. As part of the numerical results Fig. 4 gives the system energy partition: W = total work done by all external forces F_{Ai} ($i = 1....4$ number of subassembly row in the spoke), W^D = total elastoplastic deformation energy, W^K = total kinetic energy of structures in the spoke, W^F = total energy transmitted to the coolant. Fig. 5 is a plot of predicted fuel element deformations at L/2 for all four rows as a function of time.

3. Conclusion

Experimental and theoretical studies were described on the structural behavior of single and clustered LMFBR fuel elements under relevant extreme static and impulsive loading conditions. Our experience from a large number of single subassembly experiments and computer calculations with BEDYN-2 allows the following conclusions up to now:

- The elastoplastic response of a single fuel element is mainly governed by two interacting deformation modes: The duct bending and the cross section flattening with associated pin-bundle compression.
- The concept of nonlinear discrete hinges turned out to be a useful structural idealization for 2D static and dynamic cases. This is because plastic strains are essentially confined to localized regions in the cases investigated.
- BEDYN-2 permanent deformation predictions are correlating within 10 % with experimental findings from static as well as impulsive tests.

From large scale SNR-300 core model explosion tests as well as from numerical results obtained with CØRE-1 it can be stated that

- relevant FCI-type pressure pulses are causing structural damage, which is essentially limited to the first row of elements around the ruptured subassembly
- the SNR-300 core structure is capable to absorb quite high energies by moderate plastic deformations. An inherent ability to withstand severe pressure pulses has been proven experimentally and theoretically.

References

[1] L. Caldarola: A Theoretical Model with Variable Masses for the Molten-Fuel-Sodium Thermal Interaction in a Nuclear Fast Reactor, Nucl. Eng. & Design 34, No. 2, Nov.1975 pp. 181-201

[2] H. Jacobs: Die Analyse der thermischen Wechselwirkung von Brennstoff und Natrium unter Verwendung eines exakten thermo- und hydrodynamischen Modells, KFK 2260, Karlsruhe, Apr. 1976

[3] P.H. Denny, N.J.M. Rees, G.R. Warren: An Empirical Study of the Effects of a Simulated Sodium Coolant Vapour Explosion in a Subassembly of the PFR Core Structure, 2nd Int. Conf. SMIRT, paper E 1/7, London (Sept. 1973)

[4] R. Krieg, R. Liebe, H. Will, H. Zehlein: Mechanical Behavior of the LMFBR Core Structure under Transient Pressure due to Local Failure, 3rd Int. Conf. SMIRT, Invited paper E 2/1*, London (Sept. 1975)

[5] H. Will: Explosion Tests on LMFBR Core Models; An Evaluation for Reactor Safety, paper at the Conf. on Fast Reactor Safety and Related Physics, Chicago, (Oct. 1976)

[6] R. Liebe: Subassembly Experiments and a Computer Code to Analyze the Dynamic Core Deformation During Local Failure Propagation, submitted for publication in Nucl. Eng. & Design 1977

[7] R. Liebe, H. Will, H. Zehlein: Mechanical Response of LMFBR Cores under Transient Pressure Loading, 1st European Nucl. Conf., Paris (April 1975)

[8] H. Beutel, et al.: Transient Deformation of LMFBR Cores due to Local Failure: A Theoretical and Experimental Investigation, submitted for publication in Nucl.Eng. & Design 1977

[9] R. Liebe: Experimental Verification of Structural Models to Analyze the Nonlinear Dynamics of LMFBR Fuel Elements, Nucl. Engng. & Design 38, (1976) 29-41

[10] R. Liebe: Nonlinear Transient Deformation of Fast Reactor Fuel Elements under Impulsive Loading, 3rd Int. Conf. SMIRT, paper E 2/3, London (Sept. 1975)

[11] R. Liebe, H. Zehlein: Damping of the Radial Impulsive Motion of LMFBR Core Components Separated by Fluid Squeeze Films, companion paper B 2/e of this conference

[12] G.R. Warren: The Production of a Gaseous Explosion to Simulate the Thermal Interaction between Fuel and Sodium Coolant in Subassemblies of a Fast Reactor, 2nd Int. Conf. SMIRT, paper E 1/6, Berlin (Sept. 1973)

[13] T. Belytschko, A.H. Marchertas: Nonlinear Finite-Element Method for Plates and Its Application to Dynamic Response of Reactor Fuel Subassemblies, Trans. ASME, Journ. of Pressure Vessel Techn., Paper 74-NE-10, June 1974

[14] T. Belytschko, J.M. Kennedy, A.H. Marchertas: Dynamic Response of Fast Reactor Core Subassemblies, Nucl. Eng. & Design 28, 1974, p. 31-41

[15] J. Donea, S. Giuliani, J.P. Halleux: Prediction of the Nonlinear Dynamic Response of Structural Components Using Finite Elements, Nucl. Eng. & Design 37, 1 (1976) pp. 95-114

[16] G.R. Cowper, P.S. Symonds: Strain Hardening and Strain Rate Effects on the Impact Loading of Cantilever Beams; Techn. Rep. No. 28, O.N.R. Contract Nonr-562 (1o) Brown University, Prov., USA (Sept. 1957)

[17] M. A doux, F.W. Katz, W. Olbrich, E.G. Schlechtendahl: SEDAP - An Integrated System for Experimental Data Processing, KFK 1594 (EUR 4730e), Karlsruhe (Jan. 1973)

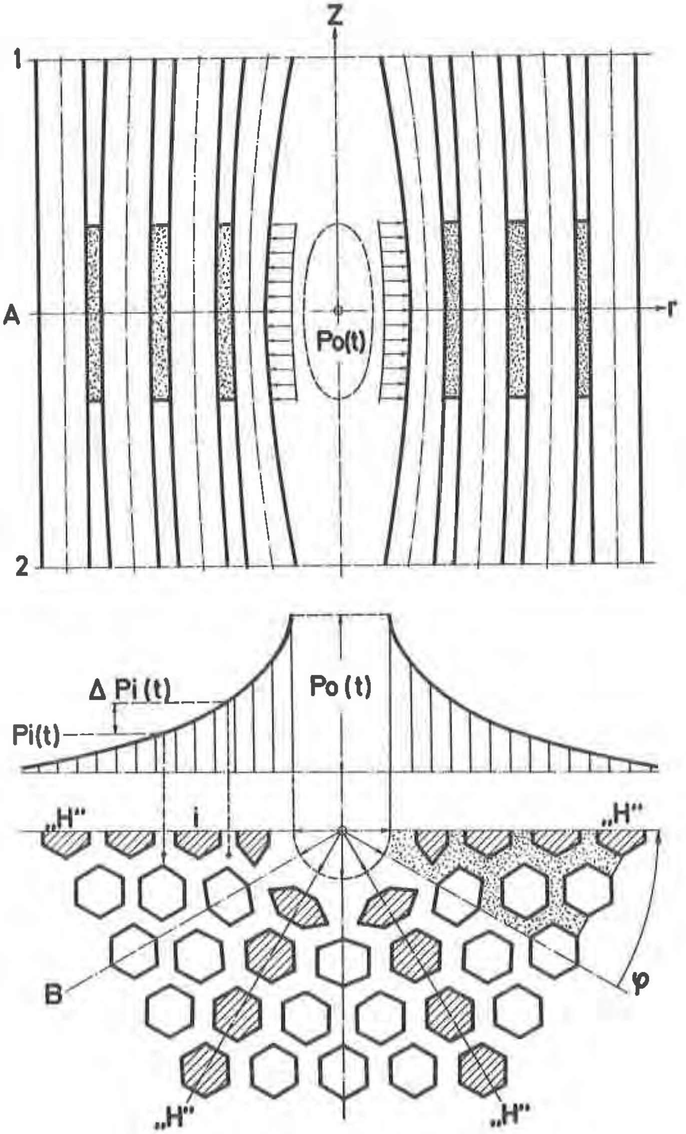


Fig. 1 Cross sections through an LMFBR core showing fuel element deformation pattern due to a transient pressure field

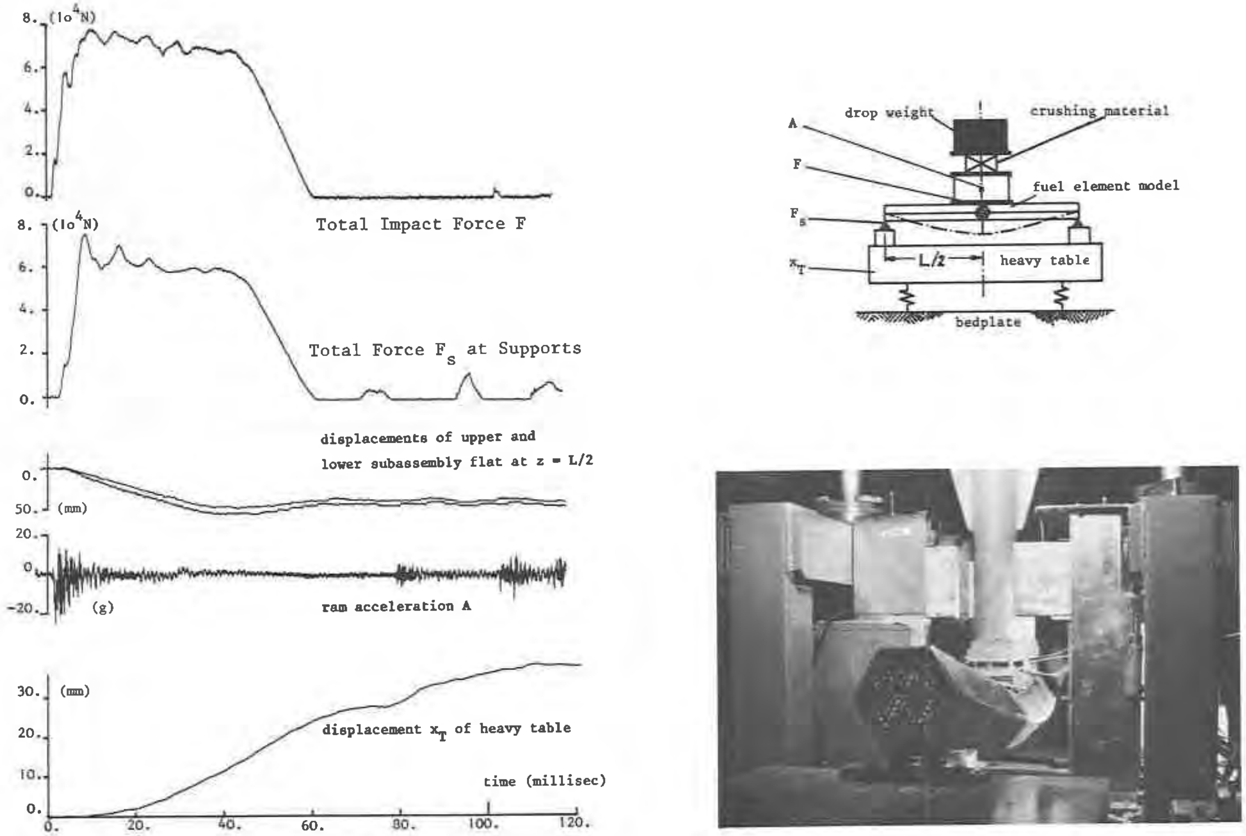
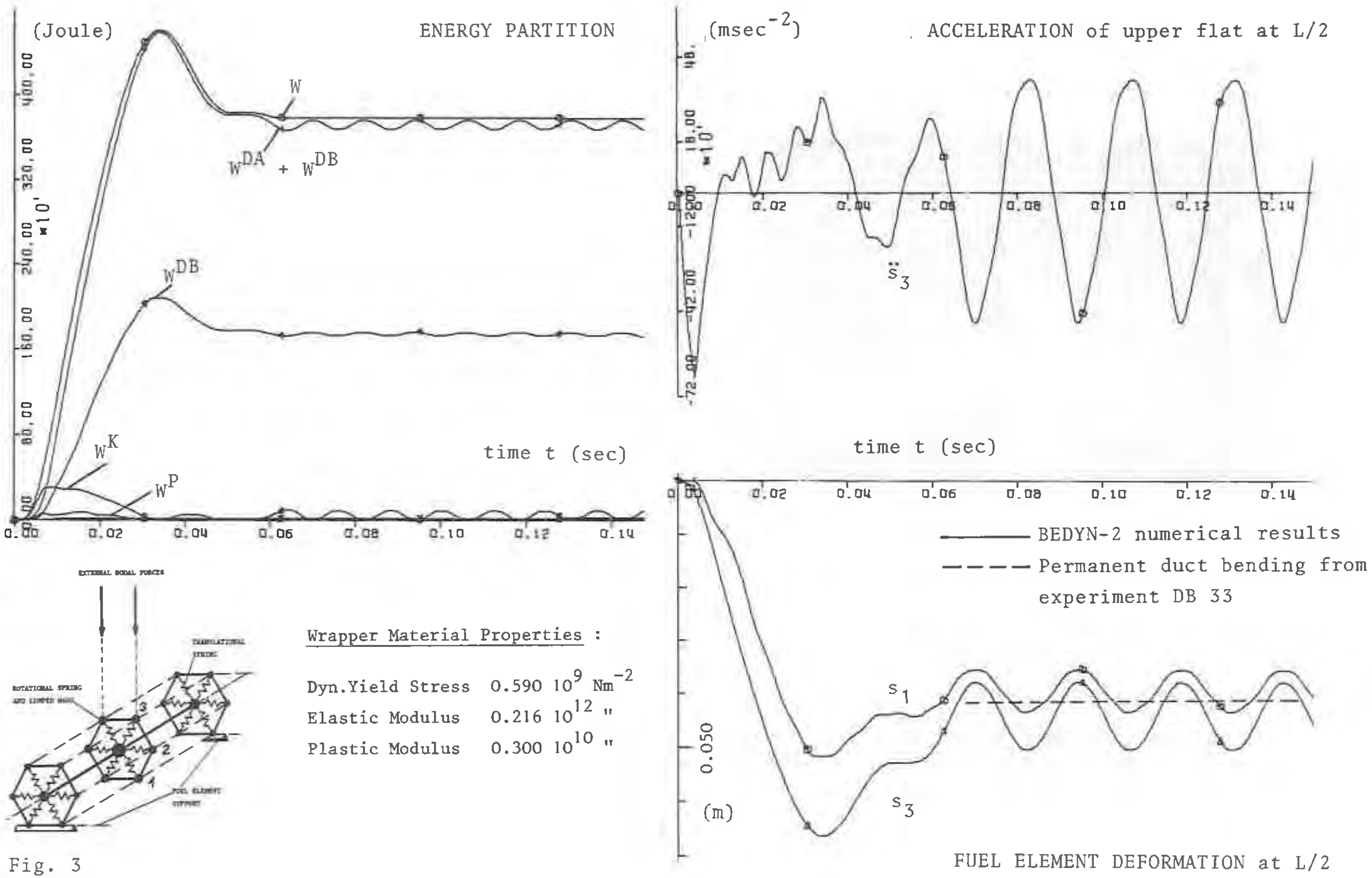


Fig. 2 Typical records of an impulsive subassembly loading experiment (test DB 33)



<u>Wrapper Material Properties</u> :

Dyn.Yield Stress	$0.590\ 10^9\ Nm^{-2}$	
Elastic Modulus	$0.216\ 10^{12}$	"
Plastic Modulus	$0.300\ 10^{10}$	"

Fig. 3

Some results of a BEDYN-2 analysis predicting the fuel element response during experiment DB 33 (see Fig. 2)

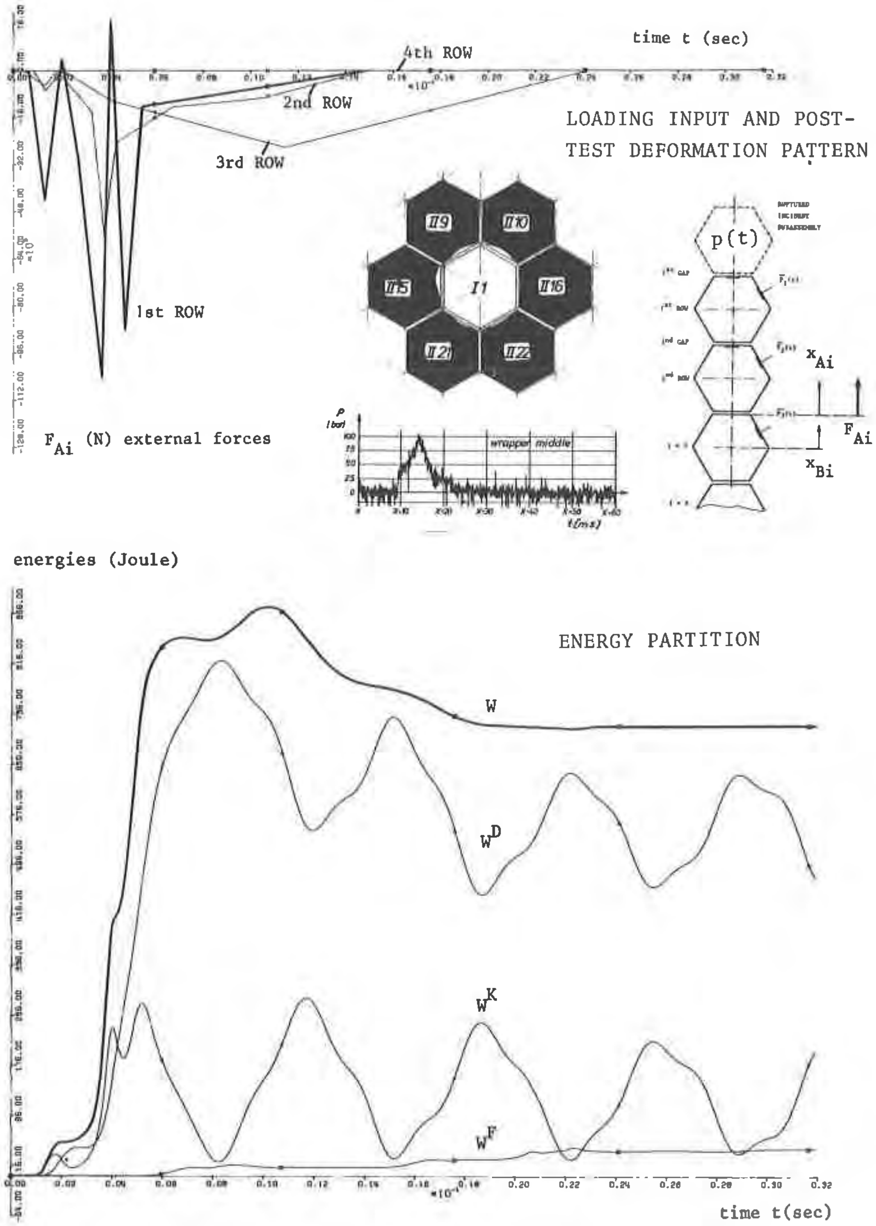


Fig. 4 Energy partition results of a CØRE-1 transient analysis of SNR-300 explosion test 3 using original pressure records as loading input

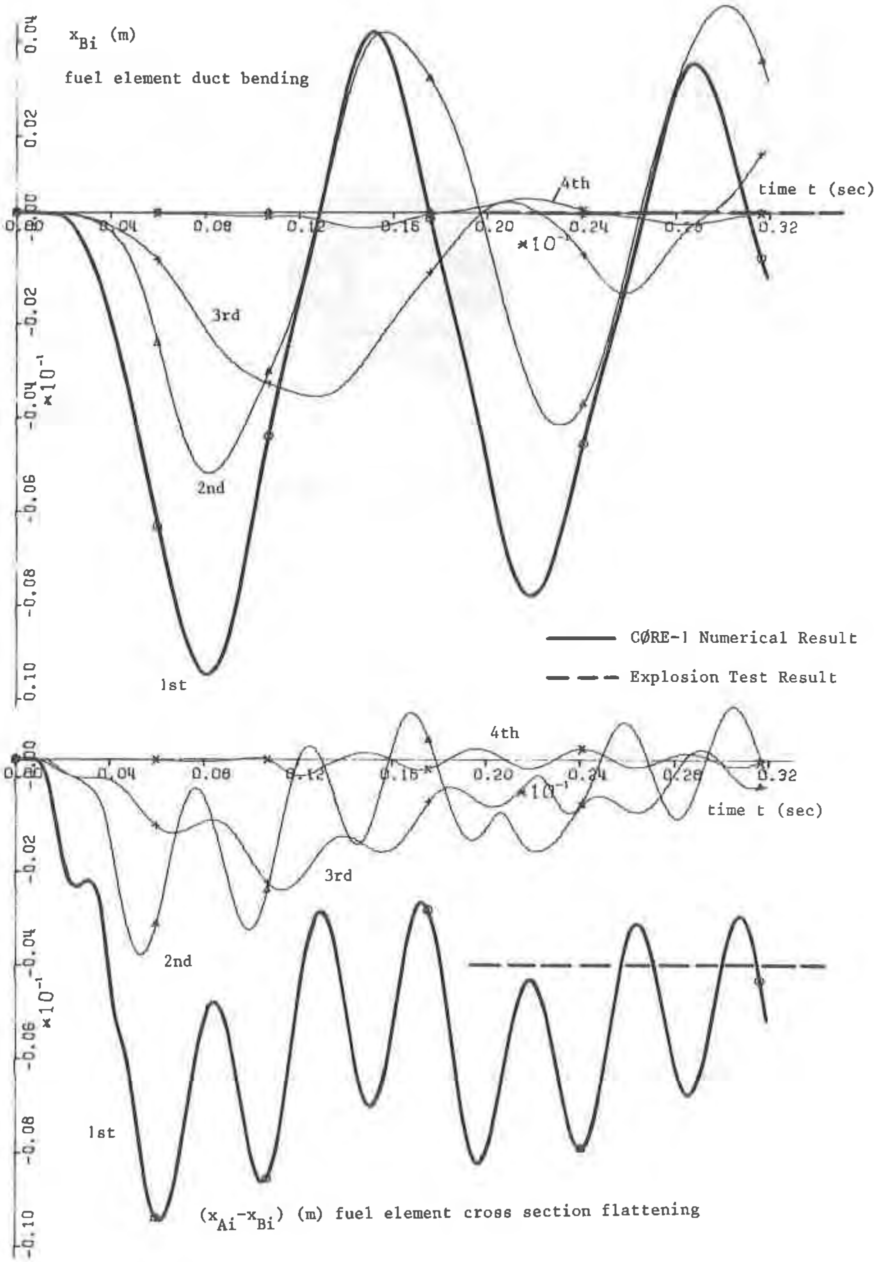


Fig. 5 Predicted elastoplastic fuel element deformations from the transient analysis of Fig. 4