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High-performance impact absorbing materials—the concept, design tools and applications

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Abstract
The concept of design of adaptive materials composed of elements with controllable yield stresses is presented and the corresponding, gradient-based numerical design tools are described. Numerical simulation of the adaptation effect to various impact scenarios is demonstrated. The crucial point to get an additional value of energy dissipation (due to synergy of repetitive use of dissipaters in honeycomb-like cellular microstructure) is to pre-design an optimal distribution of yield stress level in all controllable elements, triggering a desired sequence of local collapses. High effectiveness of active impact energy absorption by the yield stress adjustment demonstrates potential application of the concept e.g. in shock-absorbing systems.

1. Introduction

The motivation for the research undertaken is to respond to requirements for high impact energy absorption e.g. in the following cases: (i) structures exposed to risk of extreme blast, (ii) light, thin-wall tanks with high impact protection, (iii) vehicles with high crashworthiness, (iv) protective barriers etc. Typically, the suggested solutions focus on the design of passive, energy-absorbing systems. These systems are frequently based on aluminium and/or steel honeycomb packages characterized by a high ratio of specific energy absorption. Although the energy absorption capacity of such elements is high, there still remain structural members, which do not carry any load in given operation conditions of a structure. In addition, passive energy absorbers are designed to work effectively in pre-defined impact scenarios. For example, the frontal honeycomb cushions are very effective during a symmetric axial crash of colliding cars but are completely useless in other types of crash loading. Therefore distinct and sometimes completely independent systems must be developed for specific collision scenarios.

The discussed concept has been already presented at the conference *Smart Technology Demonstrators and Devices* held at Heriott-Watt University, Edinburgh, in December 2001 and the *IUTAM Symposium (Dynamic of Advanced Materials and Smart Structures)* held in Yonezawa, Japan, in May 2002.

In crashworthiness analysis of transportation vehicles there is a long list of complex phenomena: nonlinear materials (plasticity, hardening etc); nonlinear geometry (large deformations and displacements, buckling); dynamics (inertial forces); surface contacts (including self-contact of members) and strain rate effect due to the speed of the crash, just to mention some of them. In the area of crashworthiness design some initial work has been done [1, 2], but these are preliminary investigations. Other publications related to some of the phenomena present in crash events are [3–9].

In contrast to the standard passive systems the approach proposed in this paper focuses on *active adaptation* of energy-absorbing structures (equipped with sensor systems detecting impact in advance and controllable semi-active dissipaters, so-called *structural fuses*) with high ability of adaptation to extreme overloading. The quasi-static formulation of this problem allows for development of effective numerical tools necessary for further considerations concerning the dynamic problem of optimal design for the best structural response (see [10]). The structures with the highest impact absorption properties can be designed in this way. The proposed optimal design method combines sensitivity analysis with the redesign process, allowing control of stress limits in structural fuses.

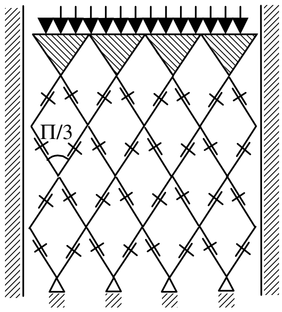


Figure 1. Trusslike micro-structure.

The so-called virtual distortion method (VDM, see [11]), leading to analytical formulae for gradient calculations, has been used in a numerically efficient algorithm. An alternative approach to a similarly formulated problem is presented in [12].

2. The concept of an adaptive multi-folding micro-structure

The objective of this paper is to propose a new concept of an adaptive micro-structure with high strain-energy-absorbing characteristics. Let us discuss the trusslike micro-structure (similar to the honeycomb layout) shown in figure 1, equipped with specially designed micro-fuses (figure 2(a)), each of which is designed as a stack of thin washers made of SMA (shape memory alloy) or piezo-material, as controllable devices (figure 2(b)). The micro-structure response to external pressure strongly depends on the yield stress levels applied to the micro-fuses and these levels can be controlled by activating a proper number of SMA micro-washers in each stack. Assume that with no washers active the compressive force able to start the yielding process in the micro-fuse is P_1 (figure 2(b)). With one washer activated, the force P_2 necessary to start yielding is smaller than P_1 (figure 2(c)). Activating two washers lowers the yielding force to $P_3 < P_2$.

To analyse the performance of the proposed micro-structure, let us follow the response of the model shown in figure 3, corresponding to behaviour of one column of the discussed hypothetic smart material.

Assuming an idealized truss structure model (figure 3(a)) composed of idealized elasto-plastic members with the shown yield stress levels (realized through properly activated fuses), the sequence of collapse is shown in figures 3(b)–(d), respectively. The corresponding effect of energy dissipation (figure 3(f)) is over 300% higher than for the same kind of micro-structure made of the same material volume and with homogeneously distributed yield stress levels. As a consequence, when compressing forces in all members of the idealized trusslike structure shown in figure 3(a) are the same, all members with the stress limit level σ_2 start to yield first, converting the structure into the configuration shown in figure 3(b). Then the yield stress level for elements marked σ_3 is lower than for tripled elements (with stress limit $2\sigma_1 - \delta$) and the consequent structural configuration is that shown in figure 3(c). Following the same procedure the next configurations, i.e. figures 3(d) and (e), can be reached.

The crucial point to get the additional value of energy dissipation (due to synergy of repetitive use of dissipaters) is to pre-design an optimal distribution of yield stress levels in all fuses, triggering a desired sequence of local collapses. Let us call the discussed adaptive micro-structure the *adaptive multi-folding micro-structure* (MFM).

The piece-wise linear constitutive model of the MFM (applicable in computational simulations), shown in figure 4, can be proposed. Cyclically loaded and unloaded adaptive members will have their characteristics with high hysteresis (figure 4(b)). Additionally, fictitious members (dotted lines in figure 4(a)) with piece-wise linear locking properties (figure 4(c)) are proposed to model the variable contact problem in the loading scenario. The numerical model for simulation of MFM performance will require taking into account both physical and geometrical nonlinearities.

Note that the resultant characteristic (figure 3(f)) of the MFM model is not unique. Playing with the yield stress level distribution, the final shape of this curve can be modified according to our requirements.

3. Numerical simulation

It is necessary to simulate numerically the MFM performance to design desired yield stress levels in all fuses. Ignoring large deformations for now, let us introduce notation of strains and stresses (cf [11]) as a superposition of linear structural response (ε_i^L and σ_i^L, respectively) to external load p and the component caused by *virtual distortions* β_j^0 modelling real, *plastic-like* distortions in adaptive members (a set B_σ of elements) plus *locking-like* distortions in fictitious members

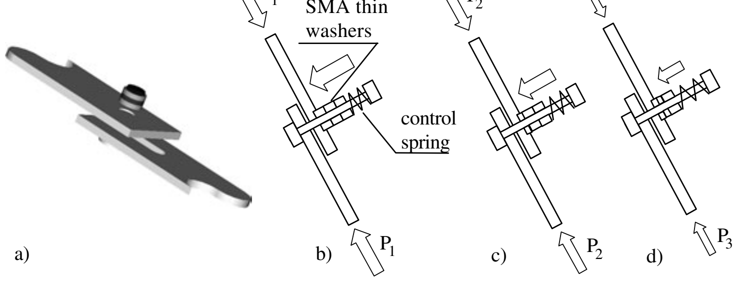


Figure 2. Controllable micro-fuses.

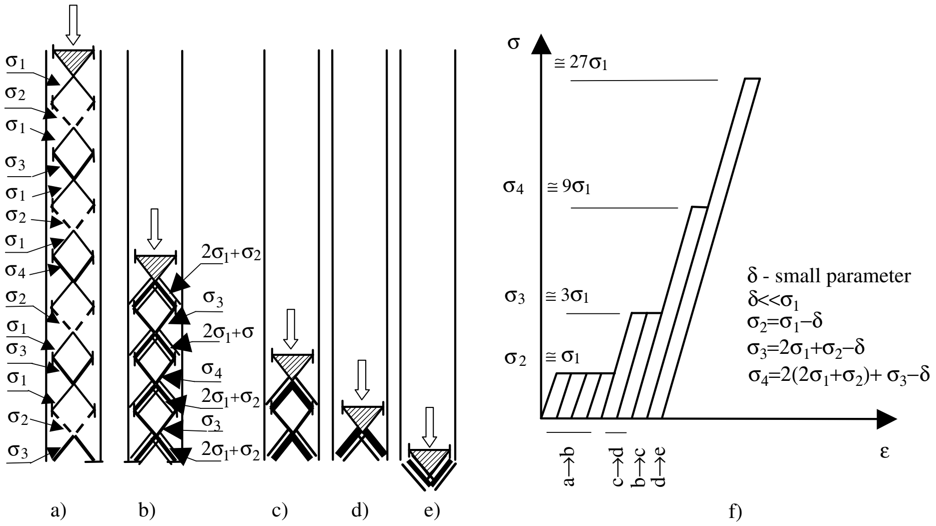


Figure 3. Model of adaptive multi-folding micro-structure (MFM).

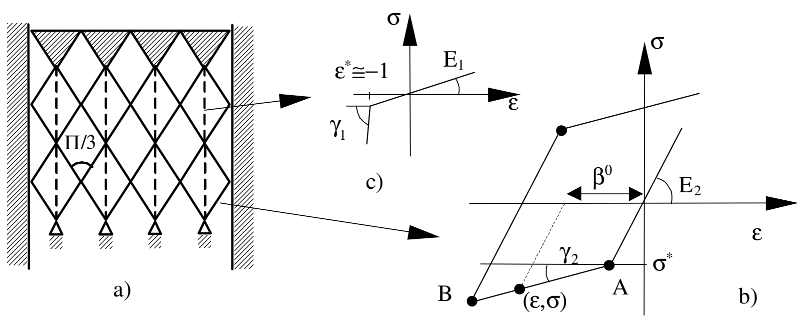


Figure 4. Constitutive model of micro-structure.

(a set B_ε of elements), simulating variable contact conditions in the loading process (cf figure 4).

$$\varepsilon_i = \varepsilon_i^L + \sum_j D_{ij}\beta_j^0 \qquad \sigma_i = \sigma_i^L + \sum_j E_i(D_{ij} - \delta_{ij})\beta_j^0 \quad (1)$$

where virtual distortions β_j^0 have to satisfy the following conditions:

$$\sigma_i - \sigma_i^* = \gamma_i E_i(\varepsilon_i - \varepsilon_i^*) \qquad (2)$$

and D_{ij} denote strain caused in members i by the unit virtual distortions $\beta_j^0 = 1$ generated in members j. Equation (2) describes plastic behaviour (line AB in figure 4(b)). Assume that for adaptive elements ($i \in B_\sigma$) γ_i is a small positive value modelling behaviour close to ideal plasticity while for fictitious elements ($i \in B_\varepsilon$) γ_i takes large negative values modelling behaviour close to locking material. $\sigma_i^* = E_i \cdot \varepsilon_i^*$ denotes the yield stress level for the adaptive members while ε_i^* (equal to -1 in our case) denotes the locking level for the very flexible fictitious members ($E_i \cong 0$).

Substituting (1) into (2), the following set of equations determining virtual distortions, modelling the MFM response to external load, can be obtained.

$$[(1 - \gamma_i)D_{ij} - \delta_{ij}](\beta_j^0 + \Delta\beta_j^0) = -(1 - \gamma_i)(\varepsilon_i^L - \varepsilon_i^*). \quad (3)$$

The above description for the geometrically linear problem is valid locally in the vicinity of the current σ–ε state. In our case, however, due to large deformations and the necessity of sequential modification of the global stiffness matrix, the incremental approach has to be applied.

The algorithm for simulation of the MFM (with determined yield stress levels σ_i^*) non-linear response to external load is shown in table 1.

The VDM-based approach for the case of large deformations is not yet ready and therefore the classical method of analysis of large deformations for elasto-plasticity is applied to determine $\Delta\beta_i^0$ in point 3 of table 1.

4. Optimal control

The non-linear analysis described above allows for simulation of performance of the MFM micro-structure with determined stress levels, triggering plastic-like behaviour of micro-fuses. However, in order to improve the MFM response adapting to a particular load, a control strategy should be proposed, where the triggering stress levels σ_i^* are control parameters.

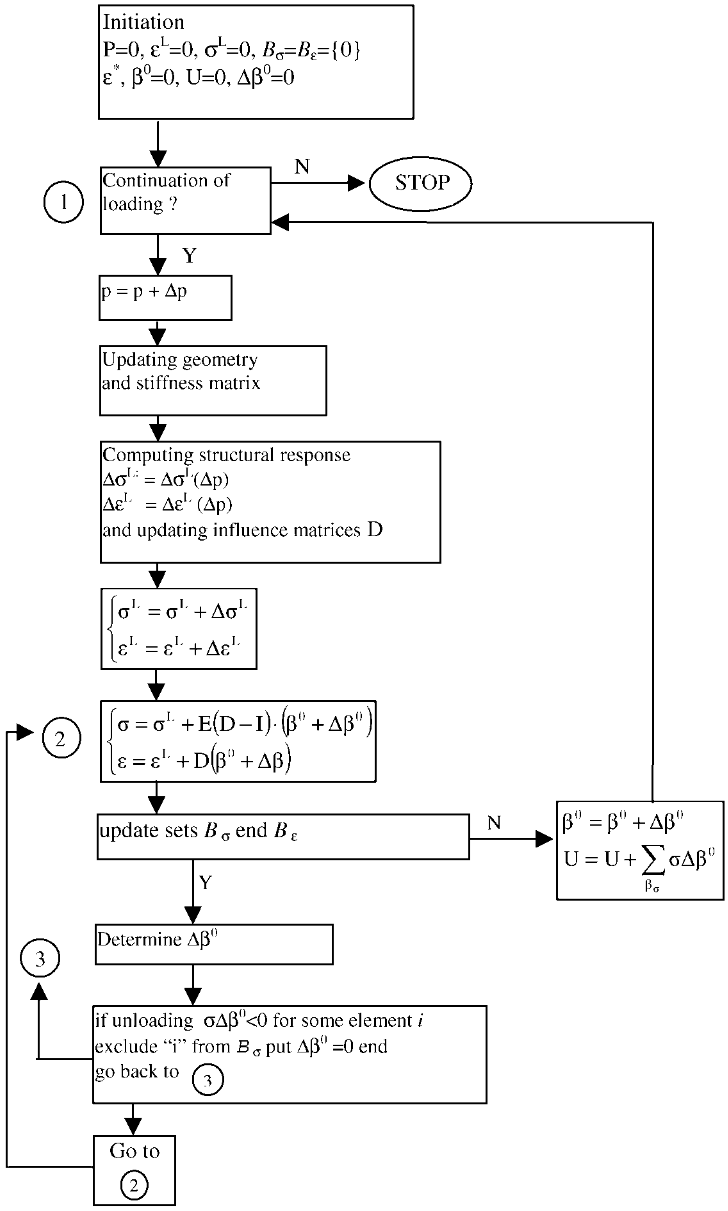
The problem can be formulated as follows. For a given load maximize the plastic-like energy dissipation,

$$\max U^0 = \sum_i \sigma_i \Delta\beta_i^0 \qquad (4)$$

subject to the following constraints:

$$|\beta_i^0| \leqslant \beta^u, \qquad \sigma^* \leqslant \bar{\sigma} \qquad (5)$$

Table 1. Algorithm for simulation of MFM non-linear response.



where σ_i is coupled with strains and the control parameters through relations (1) and (2). The solution of this quasi-static problem will allow maximally smooth load reception. Analogous formulation can also be applied to the fully dynamic problem with the accumulated energy dissipation as the objective function. The solution of the above static problem exists if the external load intensity is not higher than the maximal safe load level.

The procedure to determine this maximal load level, still safe for the adaptive micro-structure, can be proposed when the MFM with initially determined triggering stresses ($\sigma_i = \bar{\sigma}$) is not able to sustain the applied load with assumed constraints $|\beta_i^0| \leqslant \beta^u$ imposed on plastic distortions. Then, the algorithm (table 2) of adaptation (mostly lowering) of the control parameters σ_i^* can be applied, where maximization of the energy dissipation U has been chosen as the control strategy.

For the small-deformation case the gradient-based procedure of MFM adaptation can be driven by the following, analytically determined formulae, obtained from equations (3):

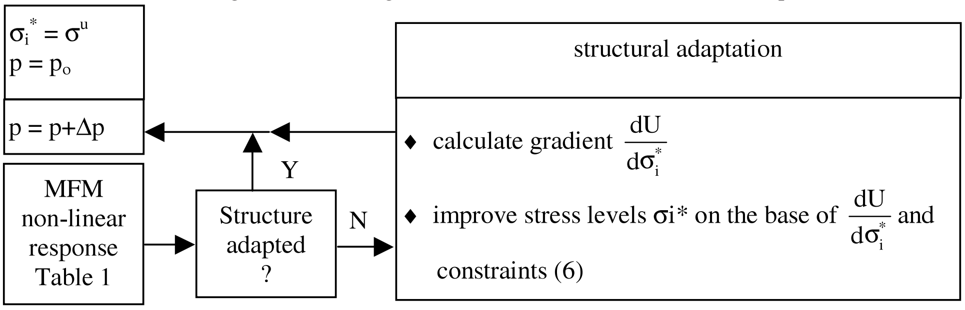
$$[(1-\gamma_i)D_{ij} - \delta_{ij}]\frac{\partial\Delta\beta_j^0}{\partial\varepsilon_k^*} = (1-\gamma_i)\delta_{ik} - ((1-\gamma_i)D_{ij} - \delta_{ij})\frac{\partial\Delta\beta_j^0}{\partial\varepsilon_k^*} \tag{6}$$

where gradient $\frac{\partial\beta_j^0}{\partial\varepsilon_k^*}$ was calculated for the previous load level.

Having the relation for actual strains

$$\varepsilon_i = \varepsilon_i^L + \beta_i^0 + \Delta\varepsilon_i^L + \sum_j D_{ij}\Delta\beta_j^0 \tag{7}$$

Table 2. The algorithm searching for the maximal load level safe for an adaptive MFM.



the corresponding gradient relations can be provided:

$$\frac{\partial \varepsilon_i}{\partial \varepsilon_k^*} = \frac{\partial \beta_j^0}{\partial \varepsilon_k^*} + \sum_j D_{ij} \frac{\partial \Delta \beta_j^0}{\partial \varepsilon_k^*}. \tag{8}$$

Analogously

$$\frac{\partial \sigma_i}{\partial \varepsilon_k^*} = E_i \sum_j (D_{ij} - \delta_{ij}) \frac{\partial (\beta_j^0 + \Delta \beta_j^0)}{\partial \varepsilon_k^*}. \tag{9}$$

Finally, the gradient of the objective function (4) can be calculated as follows:

$$\frac{\partial U}{\partial \varepsilon_k^*} = \sum_i \left(\frac{\partial \sigma_i}{\partial \varepsilon_k^*} \Delta \beta_i^0 + \sigma_i \frac{\partial \Delta \beta_i^0}{\partial \varepsilon_k^*} \right) \tag{10}$$

where $\Delta\beta_i^0$ is determined by operation 3 in table 1, $\frac{\partial \Delta\beta_i^0}{\partial \varepsilon_k^*}$ is determined by (6) and $\frac{\partial \sigma_i}{\partial \varepsilon_k^*}$ is determined by (9).

Following the nonlinear incremental analysis of MFM response (for fixed σ_i^* parameters) described in table 1, the solution for $\Delta\beta_j^0$ (from equation (3) in the case of small deformations) for each load level is needed. With small extra cost (modifying right-hand side vectors) derivatives $\frac{\partial \Delta\beta_i^0}{\partial \varepsilon_k^*}$ can be determined (cf (6)) and stored. Afterwards the gradients (10) can also be computed and accumulated step by step. Finally having global structural response and the gradient (10) value, the decision about modification of control parameters σ_i^* can be taken.

The VDM-based approach to sensitivity analysis for the case is not yet ready and therefore gradients (10) are calculated with the finite difference approach.

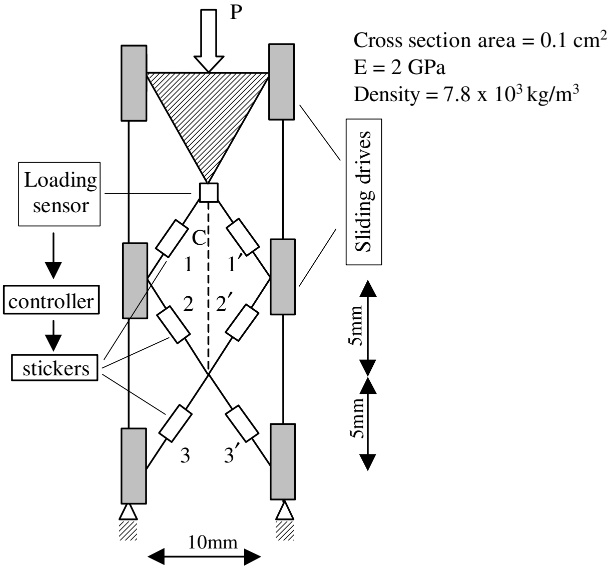


Figure 5. MFM demonstrator set-up.

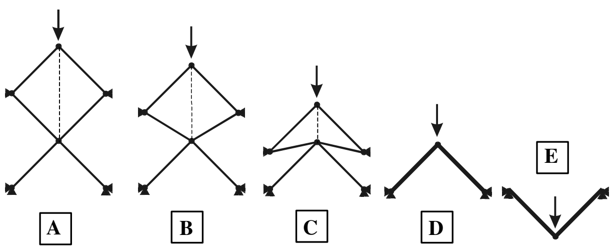


Figure 6. Desired multi-folding sequence.

5. Numerical example

A numerical model of the MFM demonstrator set-up (figure 5) has been created and tested. The model consists of six elements with identical cross section ($A = 1\ \mathrm{cm}^2$) and material properties ($E = 2$ GPa, density 2×10^3 kg m^{-3}). Contact element 'C' provides correct model behaviour.

The objective function (4) distribution as the quasi-static structural response to external static load $P = 30$ kN, for two control parameters (selected systematically), σ_1^* describing the yield stresses for elements 1, 1′, 3 and 3′ and σ_2^* describing the yield stresses for elements 2 and 2′, is shown in figure 7. Extreme plastic energy dissipation is associated with optimal folding sequence A–E (figure 6).

The evolution of stresses, strains and plastic distortions for selected elements 1 and 2, corresponding to the optimal control parameters $\sigma_1^* = 60$ MPa and $\sigma_2^* = 50$ MPa (cf figure 7), are shown in figures 8 and 9, respectively. Evolution of elastic and plastic energy is presented in figure 10.

The fully dynamic response of the considered model (with plastic stress limits identical to the above optimal quasi-static solution) is presented in figures 12 and 13 while the evolution of kinetic, elastic and plastic (dissipated) strain energy for the whole analysed structure is depicted in figure 11. In dynamic analysis the force P from the static case was replaced by a concentrated mass with initial velocity. The evolution of energy shows that the whole initial kinetic energy has been dissipated during the multi-folding process.

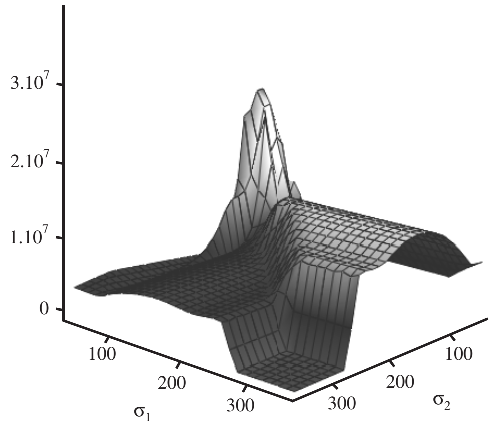


Figure 7. The energy dissipation for various yield stress values.

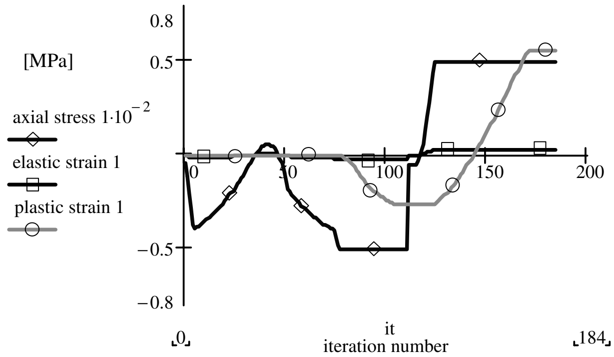


Figure 8. The evolution of stress, strain and plastic distortion for element 1.

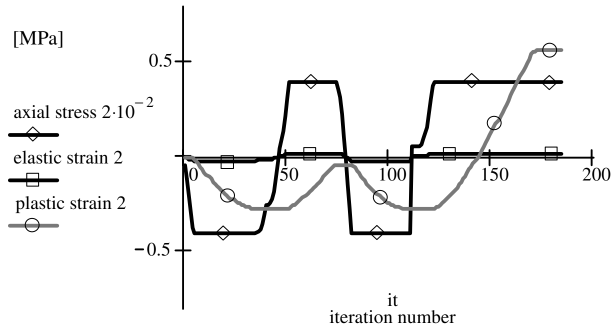


Figure 9. The evolution of stress, strain and plastic distortion for element 2.

6. Conclusions

The paper demonstrates the effectiveness of the proposed concept. The yield stress level adaptation to applied load has significant influence on the intensity of strain energy dissipation. If the structure can be decomposed into elements with their own micro-structure inside, the above approach can be applicable on the macro-structural as well as micro-structural level.

The following general methodology in design of an adaptive MFM can be proposed:

- design the topological pattern of the MFM for a variety of all expected extreme loadings;

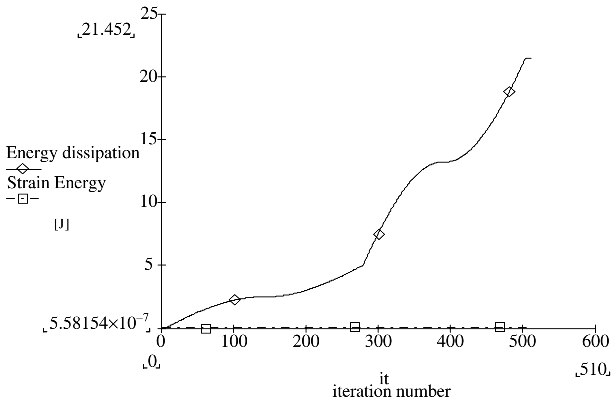


Figure 10. Evolution of elastic and plastic (dissipated) strain energy.

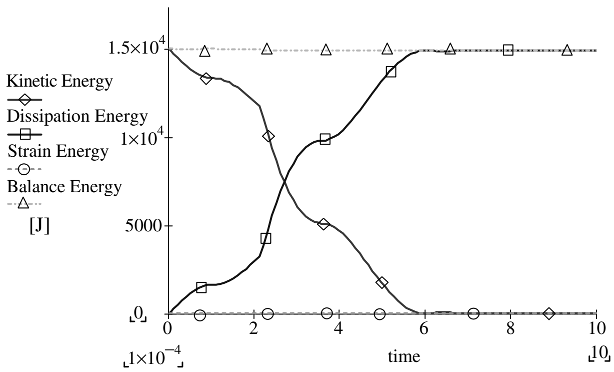


Figure 11. Evolution of energy components for dynamic response.

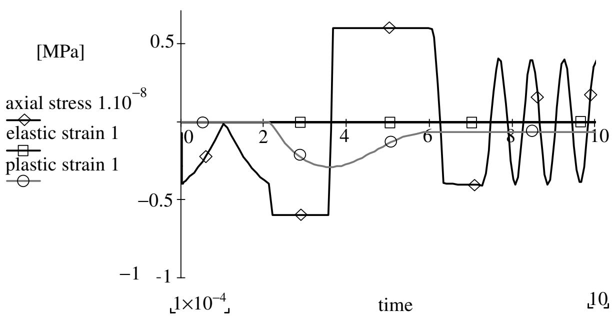


Figure 12. The evolution of stress, strain and plastic distortion for element 1.

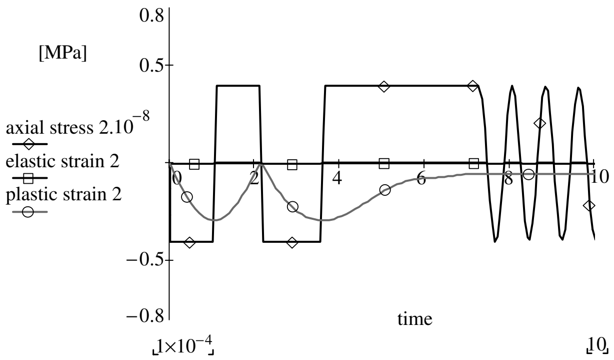


Figure 13. The evolution of stress, strain and plastic distortion for element 2.

- determine the optimal yield stress level distribution (quasi-static approach on macro-structural level, without the multi-folding effect) for each extreme loading;
- determine the optimal yield stress level distribution (quasi-static approach on micro-structural level, including the multi-folding effect) for each extreme loading;
- simulate the fully dynamic response of the adaptive MFM for each extreme loading and
- apply in real time the pre-computed control strategy as the response to detected (through a sensor system) impact.

Acknowledgments

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