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 pressures 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 micro-structure) is to pre-design the optimal distribution of yield stress level in all controllable elements, triggering desired sequence of local collapses. High effectiveness of active impact energy absorption by the yield pressure adjustment demonstrates the potential of application of the system e.g. in shock-absorbing systems.

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1. Introduction

Motivation for the undertaken research is to respond to requirements for high impact energy absorption e.g. in the following cases: i) structures exposed for 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 the aluminium and/or steel honeycomb packages characterised by a high ratio of specific energy absorption. However high is the energy absorption capacity of such elements they still remain highly redundant structural members, which do not carry any load in an actual operation of a given 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. Consequently, 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 ant 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: non-linear materials (plasticity, hardening, etc.); non-linear geometry (large deformations and displacements, buckling); dynamics (inertial forces); surface contact (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 (Mayer, *et al* [1], Díaz and Soto,

[2]), but these are preliminary investigations. Other publications related to some of the phenomena present in crash events are Neves, *et al* [3], Yuge, *et al* [4], Maute, *et al* [5], Arora, *et al* [6], Yamakawa, *et al* [7], Pedersen [8], [9].
In contrast to the standard passive systems the proposed approach focuses on *active adaptation* of energy absorbing structures (equipped with sensor system detecting impact in advance and controllable semi-active dissipaters, so called *structural fuses*) with highest ability of adaptation to extreme overloading. The quasi-static formulation of this problem allows developing effective numerical tools necessary for further considerations concerning 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 redesign process, allowing stress limits control in structural fuses. The so-called Virtual Distortion Method, (VDM, see [11]), leading to analytical formulas for gradient calculations, has been used in numerically efficient algorithm. Another approach to similarly formulated problem is presented in [12].

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

The objective of this paper is to propose new concept of adaptive micro-structure with high strain energy absorbing characteristics. Let us discuss the truss-like micro-structure (similar to honeycomb layout) shown in Fig.1 equipped with specially designed micro-fuses (Fig.2a) with stacked thin washers made of SMA (Shape Memory Alloys) as controllable stickers (Fig.2b.) The micro-structure response to external pressure strongly depends on the yield stress levels applied to micro-fuses and these levels can be controlled activating proper numbers of SMA micro-washers in each sticker.

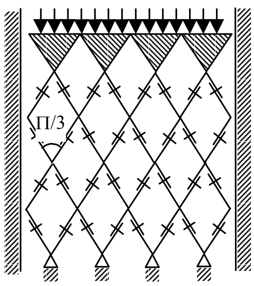


Figure 1. Truss-like micro-structure

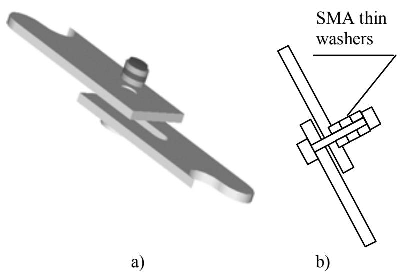


Figure 2. Controllable micro-stickers

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

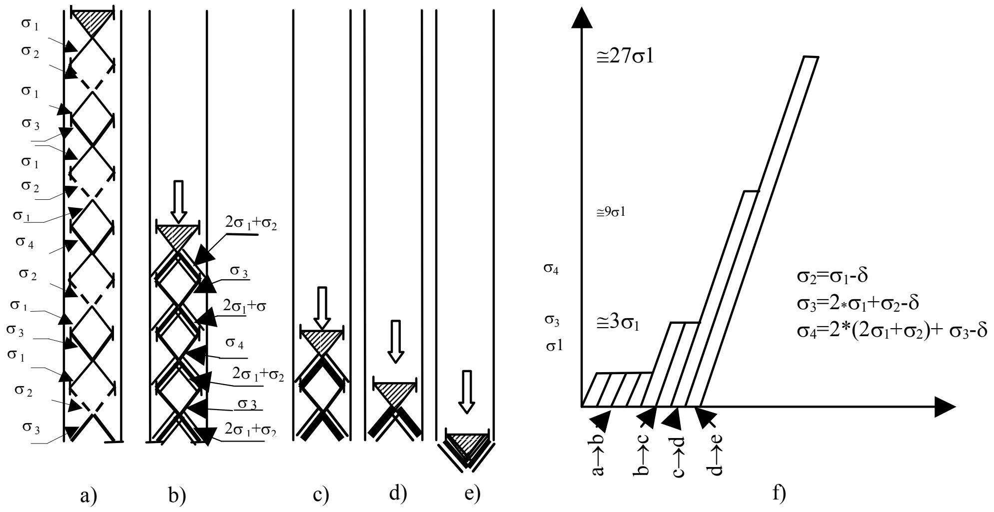


Figure 3. Model of Adaptive Multi-folding Micro-structure (MFM)

Assuming idealised truss structure model (Fig.3a) composed of idealised elasto-plastic members with the shown yield stress levels (realised through properly activated stickers), the sequence of its collapse stages is shown in Figs 3b, 3c and 3d, respectively. The corresponding effect of energy dissipation (Fig.3e) is 343% higher than for the same kind of micro-structure, made of the same material volume and with homogeneously distributed yield stress levels.
The crucial point to get the additional value of energy dissipation (due to synergy of repetitive use of dissipaters) is to pre-design the optimal distribution of yield stress levels in all stickers, triggering 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 MFM shown in Fig.4 (applicable in computational simulations) can be proposed. Cyclically loading-unloading adaptive members will have their characteristics with high hysteresis (Fig.4b). Additionally, fictitious members (dotted lines in Fig.4a) with piece-wise linear locking properties (Fig.4c) are proposed to model variable contact problem in loading scenario. The numerical model for simulation of MFM performance will require taking into account both: physical and geometrical non-linearities.

3. Numerical simulation

It is necessary to simulate numerically MFM performance to design desired yield stress levels in all stickers. To this end, let us introduce notation of strains and stresses (cf.[11]) as 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^0_j modelling real, *plastic-like* distortions in adaptive members (the set B_σ of elements) and *locking-like* distortions in fictitious members (the set B_ε of elements) simulating variable contact conditions in loading process (cf. Fig.4).

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

where virtual distortions β^0_j has 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 member *i* by the unit virtual distortion $\beta^0_j = 1$ generated in member *j*. 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 yield stress level for adaptive member while ε_i^* (equal to–1 in our case) denotes locking level for the very flexible fictitious members ($E_i \cong 0$)

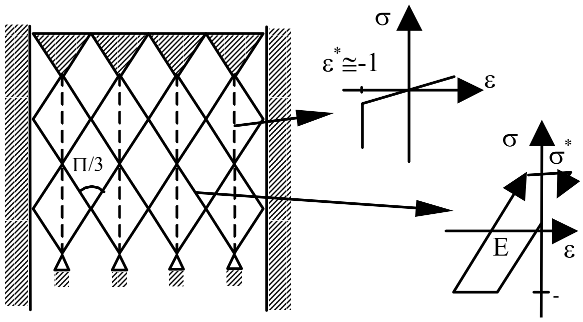


Figure 4. Constitutive model of micro-structure

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

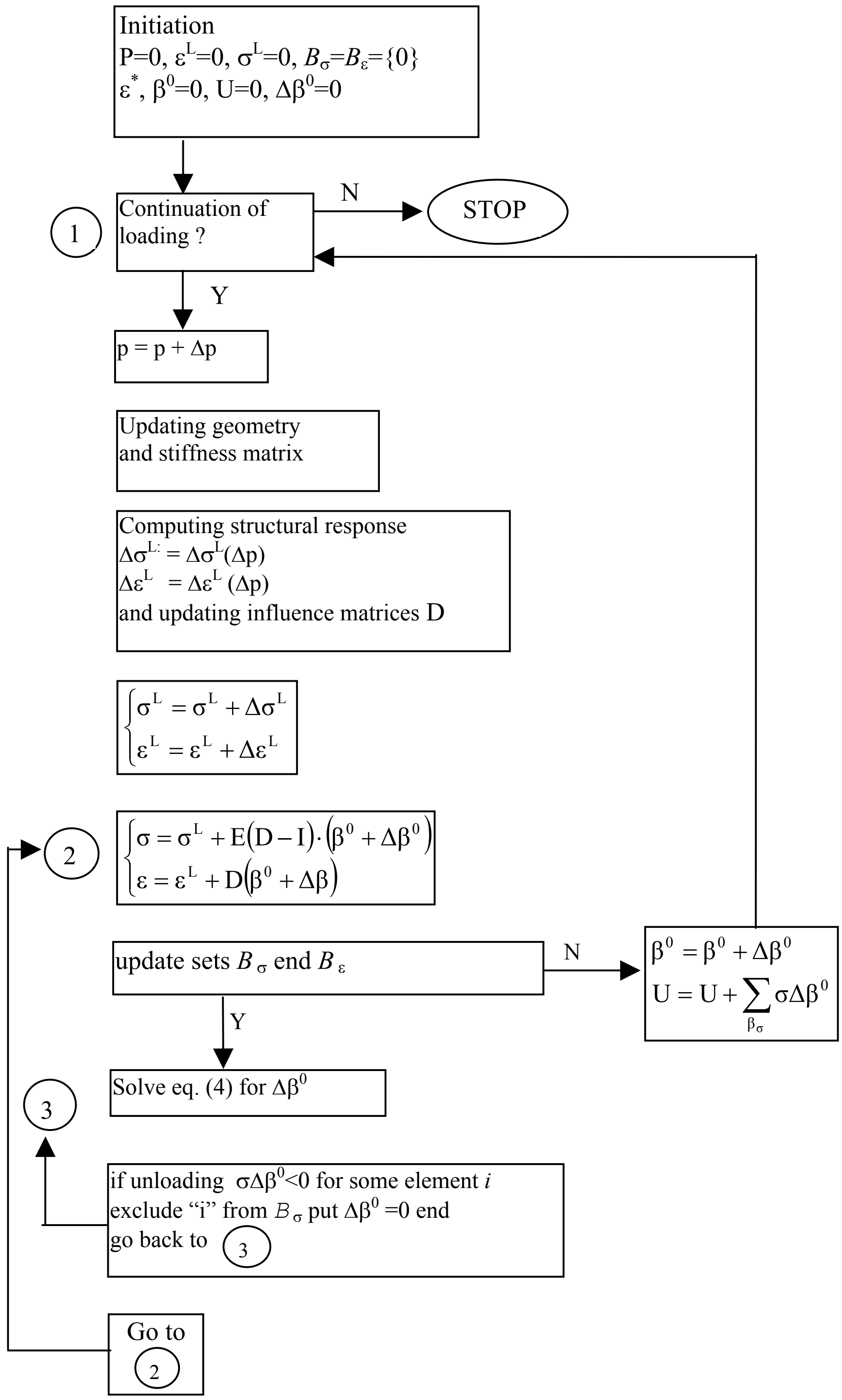
$$\left[(1-\gamma_i)D_{ij} - \delta_{ij}\right]\beta_j^0 = -(1-\gamma_i)\left(\varepsilon_i^L - \varepsilon_i^*\right) \qquad (3)$$

The above description is valid for geometrically linear problem. In our case, however, due to large deformations and necessity of sequential modification of the global stiffness matrix, the incremental approach has to be applied. Then, the set of equations (3) should be modified as follows:

$$\left[(1-\gamma_i)D_{ij} - \delta_{ij}\right]\Delta\beta_j^0 = -(1-\gamma_i)\left(\varepsilon_i^{'} + \Delta\varepsilon_i^L \frac{l_i}{l_{0i}} - \varepsilon_i^*\right) \qquad (4)$$

where l_i and D_{ij} are determined for the actual geometric configuration, $\varepsilon_i^{'}$ denotes final strains determined for previous load increment and l_{0i} denotes the initial length of the member. The VDM based algorithm for simulation of MFM (with determined yield stress levels σ_i^*) non-linear response to external load is shown in Table 1.

Table 1. VDM based algorithm for simulation of MFM non-linear response



4. Optimal control

The VDM based non-linear analysis described above allows simulating performance of the MFM micro-structure with determined stress levels triggering plastic-like behaviour of micro-stickers. However, in order to improve MFM response adapting to particular load, a control strategy should be proposed, where triggering stress levels σ_i^* are control parameters.
The problem can be formulated as follows:
for given load maximise the plastic-like energy dissipation:

$$\max U^0 = \sum_i \sigma_i \, \Delta\beta_i \qquad (5)$$

subject to following constraints

$$\left|\beta_i^0\right| \le \beta^u, \quad \sigma^* \le \overline{\sigma} \qquad (6)$$

where σ_i is coupled with strains and the control parameters trough relations (1) and (2). The solution of this quasi-static problem will allow maximally smooth load reception. Analogous formulation can be applied also 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 then the maximal safe load level.
The procedure to determine this maximal load level still safe for the adaptive micro-structure can be proposed when MFM with initially determined triggering stresses ($\sigma_i = \overline{\sigma}$) is not able to sustain

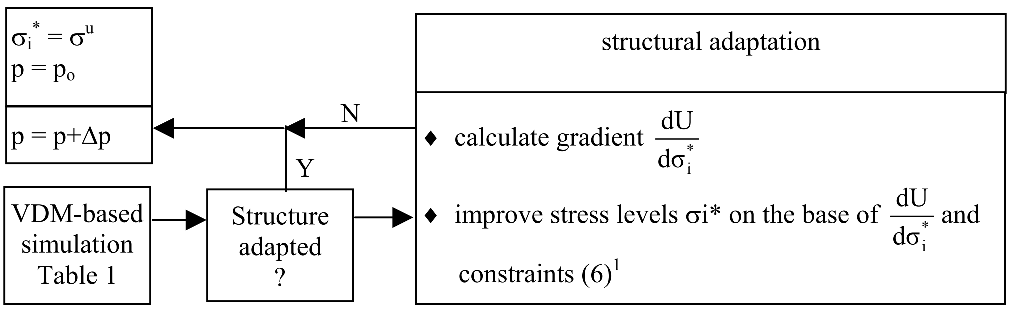


Table 2. The algorithm searching for maximal load level, safe for adaptive MFM

the applied load with assumed constraints $|\beta^o_i| \le \beta^u$ imposed on plastic distortions. Then, the algorithm (Table 2) of adaptation (mostly lowering) of the control parameters σ_i^* can be applied, where maximisation of the energy dissipation U has been chosen as the control strategy.

The gradient based procedure of MFM adaptation can be driven by the following, analytically determined formulas, obtained from equations (4):

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

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

Having the following relation for actual strains:

$$\varepsilon_i = \varepsilon_i^{'} + \Delta\varepsilon_i^L + \sum_j D_{ij}\Delta\beta_j^0 \qquad (7)$$

where $\varepsilon_i^{'}$ has been determined for the previous load level, the corresponding gradient relations can be provided:

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

Analogously

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

Finally, gradient of the objective function (5) 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 (4), $\frac{\partial \Delta\beta_i^0}{\partial \varepsilon_k^*}$ is determined by (6) and $\frac{\partial \sigma_i}{\partial \varepsilon_k^*}$ is determined by (9).

Following the non-linear incremental analysis of MFM response (for fixed σ_i^* parameters) described in Table 1, the solution of equations (4) 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) end stored. Afterwards the gradients (10) can be also step by step computed and cumulated. Finally having global structural response and the gradient (10) value, the decision about modification of control parameters σ_i^* can be taken.

5. NUMERICAL EXAMPLE

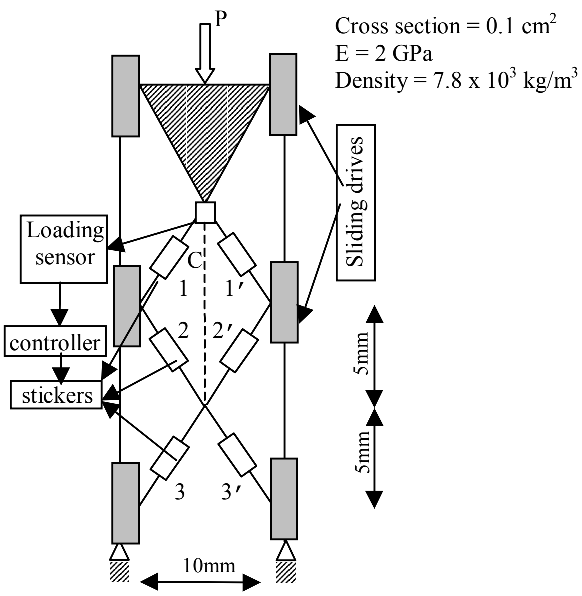


Figure 5. MFM demonstrator set-up and desired multi-folding sequence

A numerical model of the MFM demonstrator set-up (Fig.5) has been created and tested numerically.
Model consists of six spar elements with identical cross section ($A=1cm^2$) and material properties ($E=2GPa$, density $2x10^3$ kg/m^3). Using contact element „C" provides correct model behaviour.
The objective function (5) distribution as the quasi-static structural response to external static load P=30kN, for two control parameters (selected systematically): σ_1^*- describing the yield stresses for elements 1, 1', 3, 3' and σ_2^*- describing the yield stresses for elements 2, 2' is shown in Fig. 7. Extreme plastic energy dissipation is associated with optimal folding sequence A-E (Fig. 6).

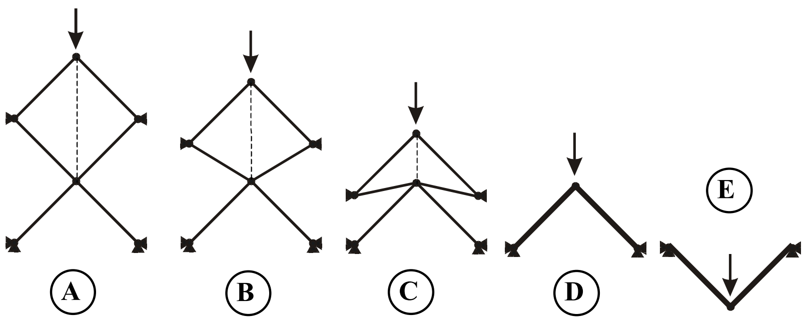


Figure 6. Desired multi-folding sequence

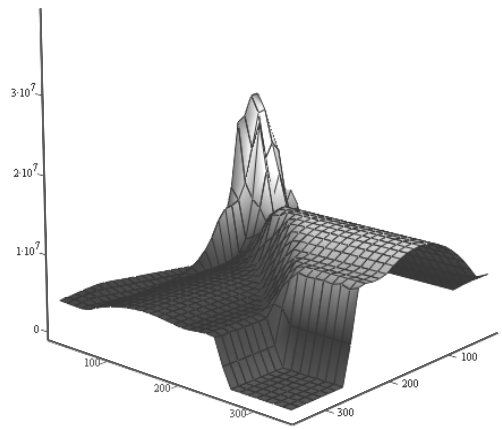


Figure 7. The energy dissipation for various yield stress values

The evolution of stresses, strains and plastic distortions for characteristic elements No.1 and 2, corresponding to the optimal control parameters $\sigma_1^*=60$ MPa and $\sigma_2^*=50$ MPa (cf.fig.7) are shown in Figs 8 and 9, respectively. Evolution of elastic and plastic energy is presented in Fig. 10

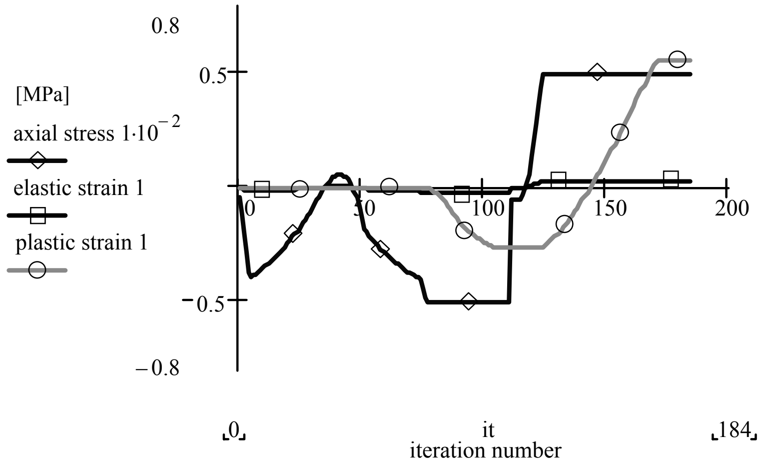


Figure 8. The evolution of stress, strain and plastic distortion for element No.1

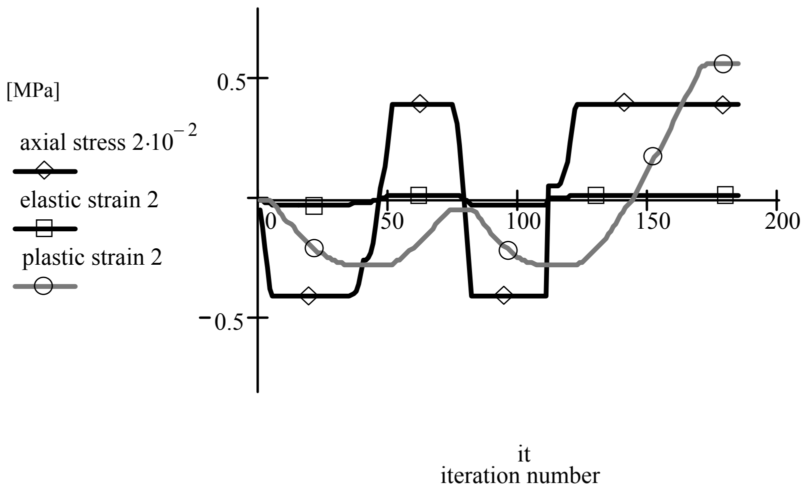


Figure 9. The evolution of stress, strain and plastic distortion for element No.2

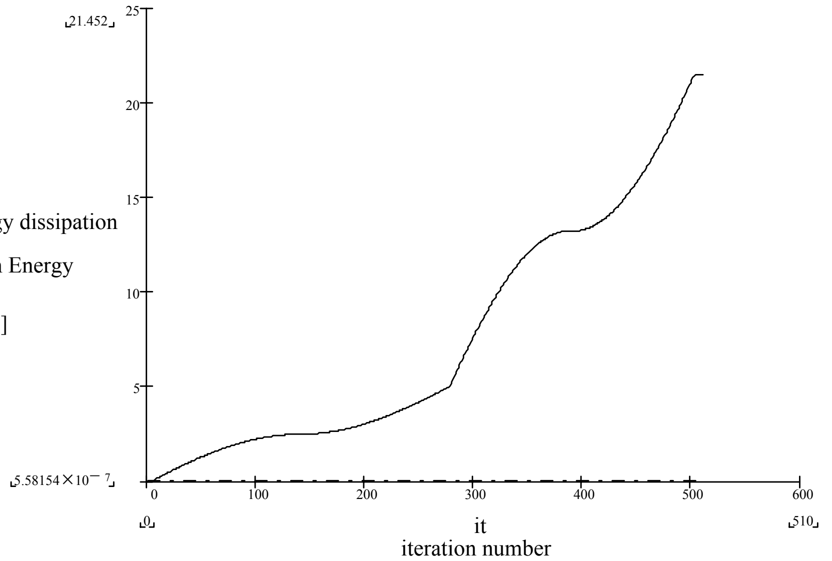


Figure 10. Evolution of elastic and plastic (dissipated) strain energy

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

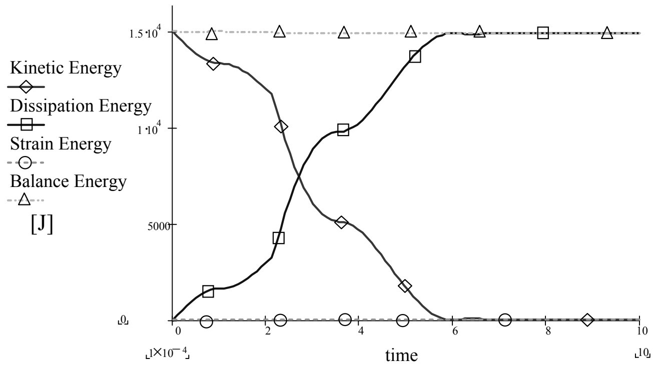


Figure 11. Evolution of energy components for dynamic response

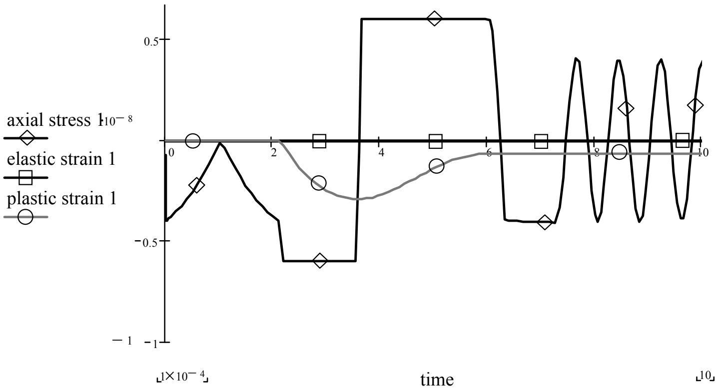


Figure 12. The evolution of stress, strain and plastic distortion for element No.1

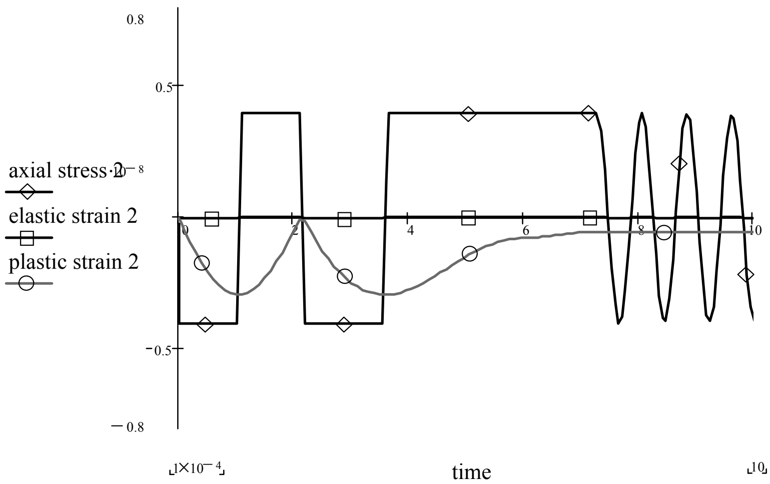


Figure 6. The evolution of stress, strain and plastic distortion for element No.2

CONCLUSIONS

The influence of the yield stress level adaptation to applied load on the intensity of energy dissipation has been demonstrated. If the structure can be decomposed into elements with 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 adaptive MFM can be proposed.

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

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