Proceedings of the
Third European Conference on Structural Control, 3ECSC,
12-15 July 2004, Vienna University of Technology, Vienna, Austria

ADAPTIVE STRUCTURES UNDER EXTREME LOADS - IMPACT DETECTION, SELF-ADAPTATION, SELF-REPAIRING

Piotr Pawłowski[1], **Jan Holnicki-Szulc**[2]

[1]*Istitute of Fundamental Technological Research, Polish Academy of Sciences, Smart-Tech Centre*
www.smart.ippt.gov.pl

The concept of design of adaptive structures equipped with elements with controllable yield pressures is presented and the corresponding, numerical design tools are described. Numerical simulation of the effect of its adaptation to various impact scenarios is demonstrated. The crucial point to get an additional value of energy dissipation is to pre-design the optimal distribution of yield stress levels in all sections, triggering desired sequence of local collapses. High effectiveness of active impact energy absorption by the yield stress adjustment demonstrates the potential of its application e.g. in shock-absorbing systems

Keywords: *crashworthiness, adaptive structures, structural optimisation*

1 Introduction

Motivation for the undertaken research is to respond to increasing requirements for high impact energy absorption in the structures exposed to the risk of extreme blast, tall and compliant offshore structures etc.

Requirements for optimal energy absorbing systems may be stated as follows:

- The system must dissipate the kinetic energy of an impact in a stable and controlled way,
- Displacements must not exceed maximal allowable values
- Extreme accelerations and forces of the impact should be reduced to the lowest, possible level.

Almost any properly designed passive systems fulfil the first two of the requirements. The third one, because of their constant constitutive force-displacement relation, can be realized only to some extent. Therefore, in most cases, commonly applied passive protective systems are only effective for a single impact scenario. In contrast to the standard solutions, 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 high ability of adaptation to extreme overloading.

The concept formulation and numerical analysis are based on the previously published papers [1] and [2].

2 The concept of adaptive structure

In order to minimize the consequences of the dynamic load, a process of structural adaptation to an impact should be carried out. The process consists of the following, subsequent stages:

- Impact detection

Impact detection is provided by a set of sensors, which respond in advance to a danger of collision (e.g. radar, ultrasonic devices) or are embedded into the structure within a small passive crush zone (e.g. piezo-sensors). Estimation of the impact energy is then based on an initial deformation of the passive zone.

- Structural adaptation

The signal from the system of sensors must be directed to a controller unit, which selects an optimal distribution of yield forces P in active zones containing elements equipped with structural fuses. Figure 1 presents a concept of the fuse, consisting of a stack of thin, shape memory (SMA) alloy washers. The yield force in the active element depends on a friction force generated in the fuse by activating a different number of washers. The initial value P_3 (without any activation) can be gradually decreased to P_2 and P_3 respectively, when one or two washers change their original shape. Because of the characteristics of the structural fuse, the active element can be modelled as elastic-perfectly plastic with controllable yield stress value.

- Self-repair

Increasing requirements for structural durability and low-level operating costs create a need for new, smart solutions. The results of an extreme dynamic load may

---

[1] Ph.D. Student, ppawl@ippt.gov.pl
[2] Professor, holnicki@ippt.gov.pl

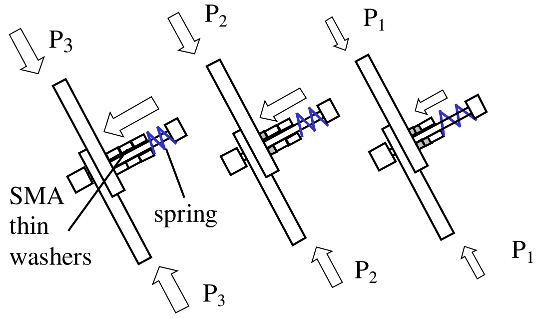

Figure 1: Controllable structural fuse

very often be fatal for a structure. In case of structures equipped with active elements, it is possible to remove residual distortions using low-level vibrations induced by an external or embedded shaker.

The following numerical example illustrates the concept of adaptive impact absorption. The example 30m high tower depicted in Fig.2, equipped with an active energy absorber, is considered. The structure is subjected to the impact of a mass of 3000kg with initial velocity of 8m/s. All structural members have a uniform cross section area and elastic modulus. The yield stress level in active elements is adjusted according to the value of the kinetic energy of the impact, while in all passive elements, is equal to 6e8Pa. Maximal, allowable strain in controlled elements is constrained to 50% of their initial length.

Objective function in the optimization problem is to minimize the horizontal acceleration of the controlled node at the top of the tower. Results for the problem for three different thresholds of yield stresses in active elements are presented in Figs. 2. For the highest threshold of 6e8Pa, response of the structure is elastic, while thresholds of 1e8 and 2.6e7Pa (optimal solution), provide permanent plastic deformation. It is clearly visible that adaptive strategy provides very significant reduction of the acceleration level and that control parameters in active elements should be adjusted according to the severity of the impact.

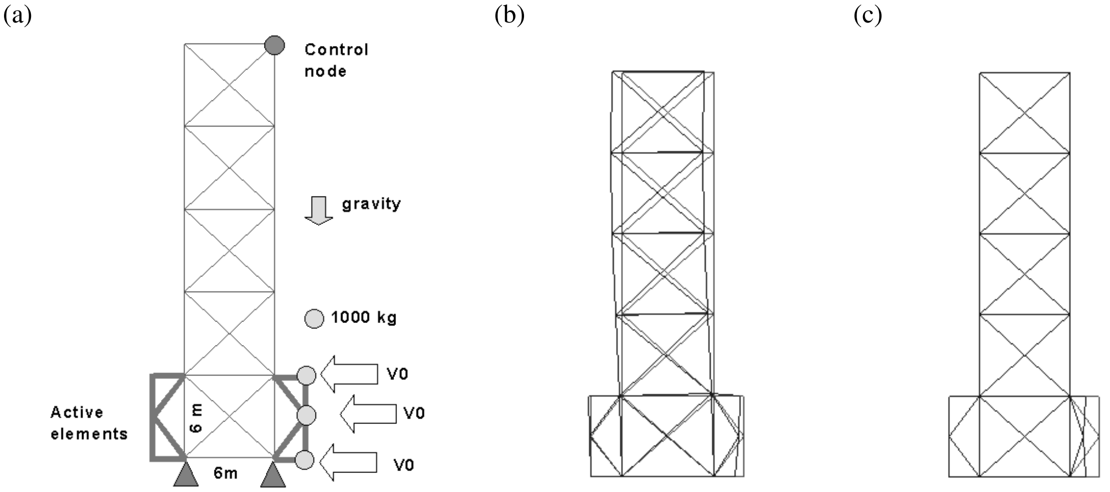

Figure 2: (a) Model of an adaptive structure, (b) displacements of the elastic solution (scaled x 1.5), (c) displacements of the optimal solution.

3 Optimal control

Two strategies of semi-active and active control might be considered. In the first strategy, yield stresses in structural members located in active zones remain unchanged during an impact. In the second one, a possibility of real-time changes in control parameters is assumed. The paper focuses only on the semi-active approach, which provides a good balance between expected results and complexity of control strategy.

A position of active elements follows from an assumption that only selected parts of the considered structure would be exposed to a danger of extreme, dynamic load. A number of active elements and their structural properties should be chosen as a result of separate optimization task.

The problem of the control may be formulated as follows: for a given structure and a given set of active elements $E_i \in A$, find optimal distribution of control yield stresses σ_i^p, minimising objective function f defined by the impact index I_2 (providing information about average acceleration level at monitored degrees of freedom (DOF) q_i^{cntrl}):

$$\min f(\sigma_i) : f \to I_2 \tag{1}$$

$$I_2 = \frac{1}{T} \sum_{t=1}^{T} \sum_{i=1}^{Ncntr} \left| \ddot{q}_i^{cntr}(t) \right| \tag{2}$$

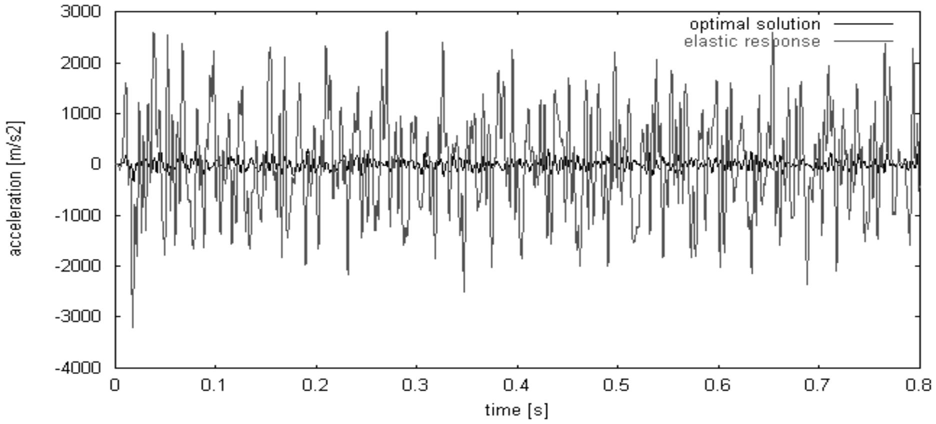

Figure 3: Horizontal acceleration of the monitored node, for the passive and the optimal plastic solution.

with following constraints, imposed on control stresses and displacements in active elements:

$$\sigma_i \in \langle \sigma_{\min}, \sigma_{\max} \rangle \tag{3}$$

$$\max\{q_i(t) \in A\} \le q_i^{\max} \tag{4}$$

Two additional measures of structural dynamic response, describing overall acceleration level in the structure and maximal acceleration values at specified DOF, may be introduced:

$$I_1 = \frac{1}{T\,N}\sum_{t=1}^{T}\sum_{i=1}^{N}\left|\ddot{q}_i(t)\right| \tag{5}$$

$$I_3 = \max_{t,i}\{\left|\ddot{q}_i^{cntr}(t)\right|\} \tag{6}$$

where *T* – time of analysis, *N* – number of DOF, *Ncntr* – number of monitored DOF.

4 Structural recovery

After optimal impact absorption, permanent deformation is localized in selected active elements. Assume that residual strain in an active element is equal to ε_i^R. Low-level vibrations induced by a shaker (external or embedded into the structure) generate strains $\varepsilon_i(t)$, which can be used to recover initial length. When residual and actual strains have opposite signs the structural fuse opens and releases accumulated distortions. In case of equal signs, the fuse remains closed:

$$\sigma_i(t) = \begin{cases} \sigma^O & if \quad \varepsilon_i(t)\varepsilon^R < 0 \quad \sigma^O - open \\ \sigma^C & if \quad \varepsilon_i(t)\varepsilon^R > 0 \quad \sigma^C - closed \end{cases} \tag{7}$$

$$\sigma^C \gg \sigma^O$$

In order to ensure stability only one active zone should be recovered at a time.

5 Numerical example

The following subsection presents an example of self-adaptation of a tall, compliant tower to a dynamic load (M=1500kg v_0=8m/s, F=20kN), followed by the process of structural recovery. The 48m high truss structure is depicted in Fig. 5a. It is assumed that an impact can take place only at specified nodes. Therefore, four active zones are located in the lower part of the structure. Values of the control yield stresses in structural fuses belong to a range of <1e5Pa, 6e8Pa>. All the passive elements have a uniform yield stress value of 6e8 Pa. The cross-section area of the active elements is 5 times bigger then in case of the passive ones. Stability of the structure is ensured by a constraint imposed on the maximal displacement of the loaded node: $q_{\max} < 0.8m$. The passive and optimal deformation (heuristic solution) with the impact indices are presented in Fig. 5a)-b)

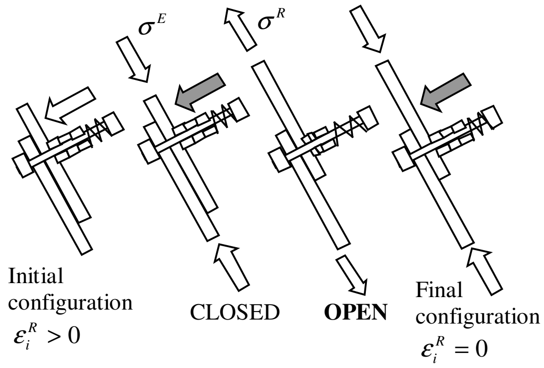

Figure 4: Structural fuse in self-repair mode

Structural recovery was performed according to the procedure described in the previous subsection. A sine-shaped, horizontal dynamic load (amplitude 8e4 N, frequency 20Hz) was applied at the support level of the structure. The values σ^C and σ^O in structural fuses were chosen as 1e6Pa and 1e3Pa, respectively. The residual distortions were subsequently removed from the active zones 1-4. The results of the self-repair are depicted in Figs. 5 d)-g).

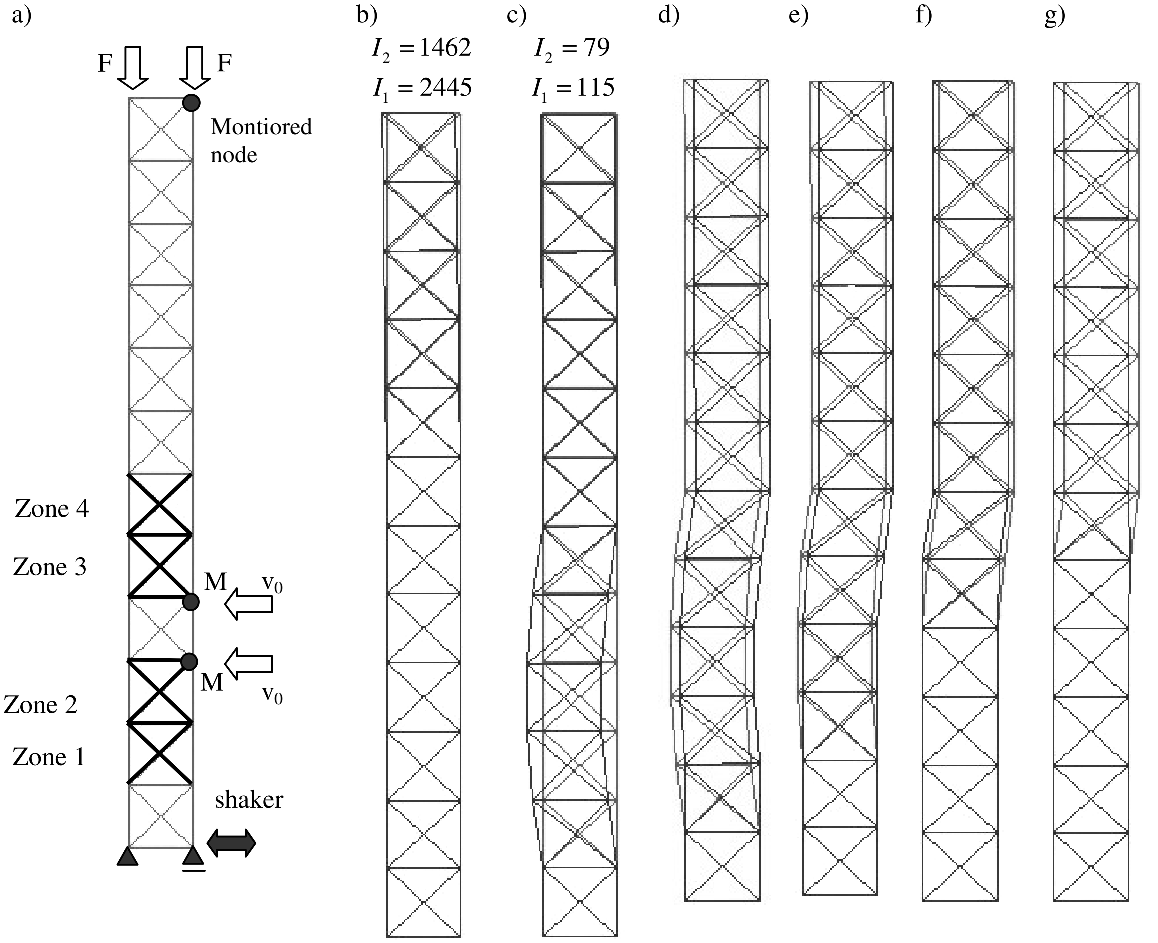

Figure 5: a) Adaptive structure, b) passive response, c) optimal solution, d) - g) structural recovery of active zones 1-4, respectively

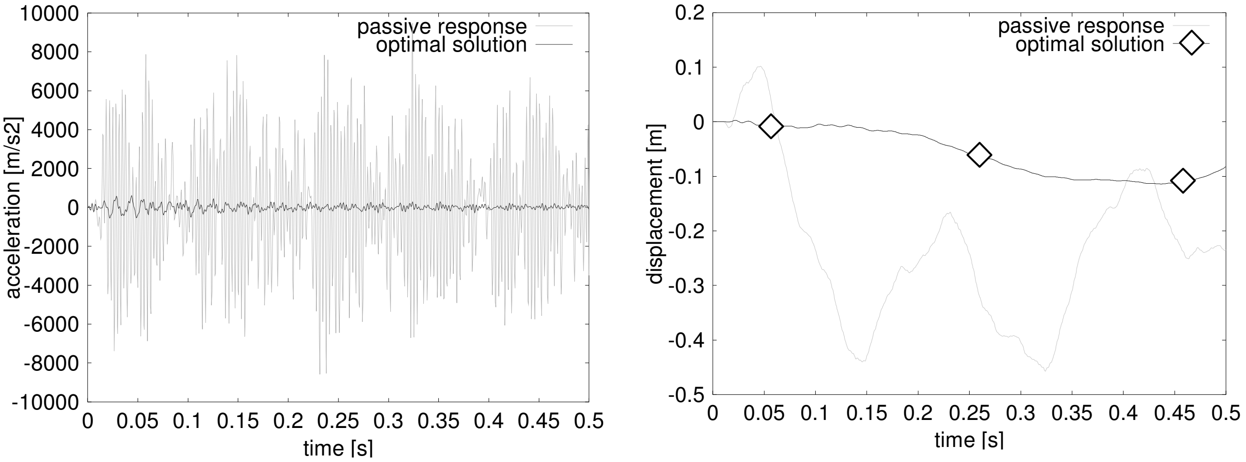

Figure 6: Horizontal accelerations and displacements of the monitored node for passive and optimal solution

6 Acknowledgments

This project was carried out within the *Research Training Network* - 6th Framework Program (HPRN-CT-2002-00284), which is thankfully acknowledged for its financial support.

7 References

[1] J. Holnicki-Szulc, P. Pawlowski , M. Wiklo*, "High-performance impact absorbing materials - the concept, design tools and applications",* Smart Materials and Structures, vol.12, number 3, 2003.

[2] J. Holnicki-Szulc, P. Pawlowski , M. Wiklo*, "Optimal Strategies of Adaptive Impact Absorption",* Proc. 5th World Congress on Structural and *Multidisciplinary Optimisation*", Lido di Jesolo, Italy,. May 19-23, 2003.