Pyro-adaptive impact energy absorber

Marian Ostrowski, Paulius Griskevicius* and Jan Holnicki-Szulc
Institute of Fundamental Technological Research, Polish Academy of Sciences Swietokrzyska 21, 00-049 Warsaw, Poland
e-mail: mostrow@ippt.gov.pl, holnicki@ippt.gov.pl
** Kaunas University of Technology, Kestucio 27,LT- 44025 Kaunas, Lithuania, e-mail: paulius.griskevicius@ktu.lt*

The paper contains a proposal of energy dissipation density controlling in lightweight thinwalled structures by reducing their crushing stiffness during an impact process. For small scale laboratory experiments, low-energy-dissipation absorber was developed. Prismatic absorber made of thin lead sheets can dissipate the impact energy at two energy density levels. Moving the concept to the real steel or aluminum structures can lead to satisfying value of the Specific Energy Absorption indicator with possible control of the energy dissipation. Experimental and FE explicit simulation results showing controllable impact process of a thinwalled prismatic absorber with rectangular crossection are presented.

Keywords: *adaptive systems, crashworthiness, impact, control applications, finite element method*

1. Introduction

Impact energy absorbing process is one of the most important challenges of present applied mechanical science. Depending of the field of use absorbers can be made for repeated or one time action use. The first group of absorbers is well known in the present state of the art, either in the controlled version where the adaptivity is quite easy to obtain. For example magneto-rheological dampers or pneumatic pistons can be used for absorption of repetitive loads [7]. The second group of absorbers still consists of only passive solutions – like crushing prismatic tubes or honeycomb panels. The main difference in crashworthiness properties of the mentioned groups is the Specific Energy Absorption (SEA) factor showing density of the dissipated energy per unit of absorber mass which takes usually higher values for the disposable absorbers. The aim of the paper is to present a feasibility study of a possible control method for the absorbers belonging to second group – a rectangular tubes. Proposed solution allows to decrease average crushing force when needed by firing pyrotechnically actioned detachable connectors which release additional members of the absorber and lead to decrease of energy dissipation.

2. Feasibility demonstrator - theoretical basis

An experimental test was performed to check real behavior of the controllable absorber concept. A rectangular absorber shape was selected due to its simplicity. The main energy dissipation mechanism in a prismatic absorber with rectangular crosssection is due to work done by traveling plastic hinges, stationary plastic hinges and material flow through the toroidal surface in the area of the crosssection edges. Energy dissipation capability of the prismatic absorbers is determined by analytical formulas developed with the macroelements method developed by Abramowicz and Wierzbicki [4,5,6]. The average crushing force P_m of the square profile can be determined by the following equation [5]:

$$P_m = \frac{\sigma_0 \cdot t^2}{4}\left(52.22 \cdot \sqrt[3]{\frac{2b}{t}}\right) \qquad (1),$$

where: σ_0 – plastic flow stress, b – length of the square side, t – thickness.
Hence, the dissipated energy is equal to the work of the average crushing force on the crushing distance:

$$E_d = P_m \delta \qquad (2),$$

where: δ - length of crushing (typically for the rectangle full crushing distance can be assumed as 80% of the initial length).
An arbitrary assumption was made: additional energy dissipating member is neglectably disturbing the length of the folding wave. Thus, simple superposition of the average dissipated energies and no interaction between absorbers can be assumed for engineering calculation. Also the length of the crosssection sides differs slightly, so when the sheet thickness is the same just one crossection parameter can be used for both absorbers. With the same crossection properties the average crushing force P_m is also the same. Hence, a total energy absorbing capability in the absorber with additional member can be expressed by:

$$E_{d\,total} = P_m \cdot (d_b + d_a) \cdot 0.8 \qquad (3),$$

where: d_b, d_a - initial length of the base profile and the additional member.
From the considerations with the simple model shown below it is apparent that additional member should not change the Specific Energy Absorption (SEA) factor for inactive case, and be able to reduce the stiffness when additional part will be decoupled.

3. Feasibility demonstrator – features

A simple experiment and FEA simulations were performed to prove the concept feasibility and perceive the weak points of the concept. In a laboratory scale test, small energies are desirable. To decrease the energy absorbing capability and crushing forces of the tested specimen (Fig. 1), a 1mm thin sheets made of lead alloy Pb1 were used. The material features were: yield stress $\sigma_Y = 8MPa$, ultimate tensile strength $\sigma_u = 21MPa$, elongation at break A5=45%, and Young's modulus $E = 14GPa$. The power law material model was used for the finite element calculations. No strain rate hardening formulation was used.
A room-scale impact hammer testing stand was used. The head of the 37kg hammer was dropped from a one-meter height onto the top of the absorber. The estimated velocity at point of first contact with the specimen was 4.47 m/s. Basing on shown below simplified calculation methodology, the total absorbed energy of the considered laboratory lead absorber is 195 J for the base member and 371 J for the assembly. The potential energy of the hammer was 370 J to the point of first contact with the absorber.
Initialization of the pyrotechnical material was performed by a custom designed computer controlling, high voltage initiation system. The initiator made as an exploding bridge wire type (EBW), was initiating 0.3g of black powder closed in an explosion chamber. Rapidly increasing pressure was opening the pyroconnection destroying sheared bolts made of soldering alloy. The capacitors battery was charged to the 311V voltage and rapidly discharged through the initiator wire on the triggering signal coming form the controlling computer. Initiating wire exploded in time shorter than 250 μs after receiving the signal form the real-time system powered by the NI Lab View software. Micro explosions were controlled by an electrical control circuit optically separated from the computer and using SCRs to fast response switching. Eight independent control channels were used.

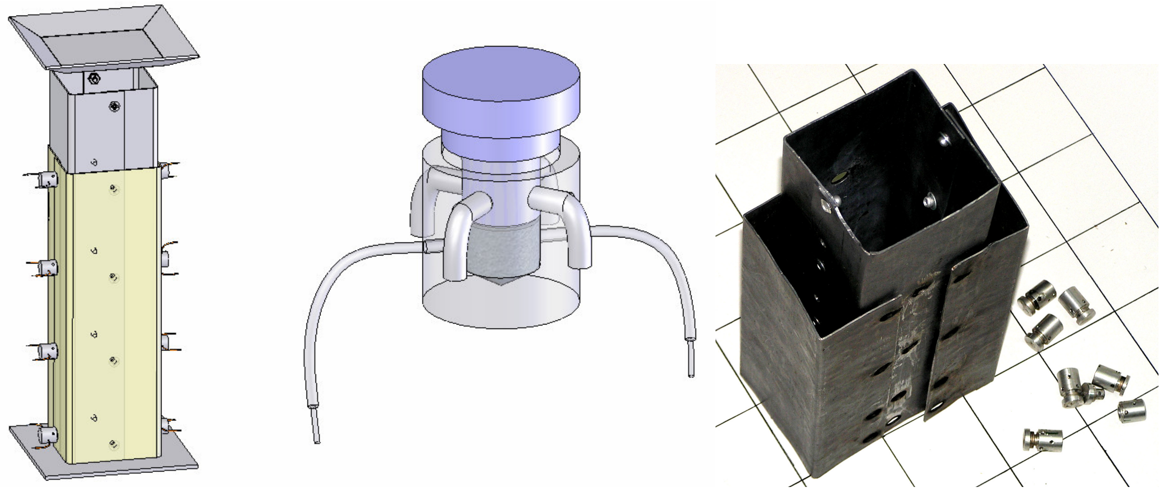

Figure 1. Lead absorber and experimental pyroconnections

4. Research

FE analysis and experimental study were performed parallely in finite elements and experimental way. Two cases were tested: the passive impact test and the active impact test when the pyroconnections were fired in prescribed time. FE model was simulated in explicit dynamics environment LS-Dyna v970.

Passive mode test was performed as a typical dropping hammer crash test. The absorber was placed on the rigid base and was being hit by the moving head of the hammer. Acceleration sensor was measuring the deceleration of the impacting mass. Fast digital camera pictures were taken with 1000 frames per second speed. All connections were closed through the whole test time.

Active mode test was conducted in the same conditions as the passive one. Photocell was switched on by the dropping head of the hammer triggering the ignition time, controlled by real time computer with a time offset. Statistical dispersion of explosion times was one of the main problems at early stage of the tests. An average delay time between initiation and explosion was 3-5ms.

Finite element deformation results were shown in figure 2. Decelerations of the head of the hammer were shown in figure 5. It is clear that the difference between the levels of deceleration is sharp and the recorded response is typical as for the crushing of thinwalled rectangular crosssection [5]. A graph of internal energies versus time function is shown in figure 8, showing 35 per cent decrease in energy dissipation for the active mode.

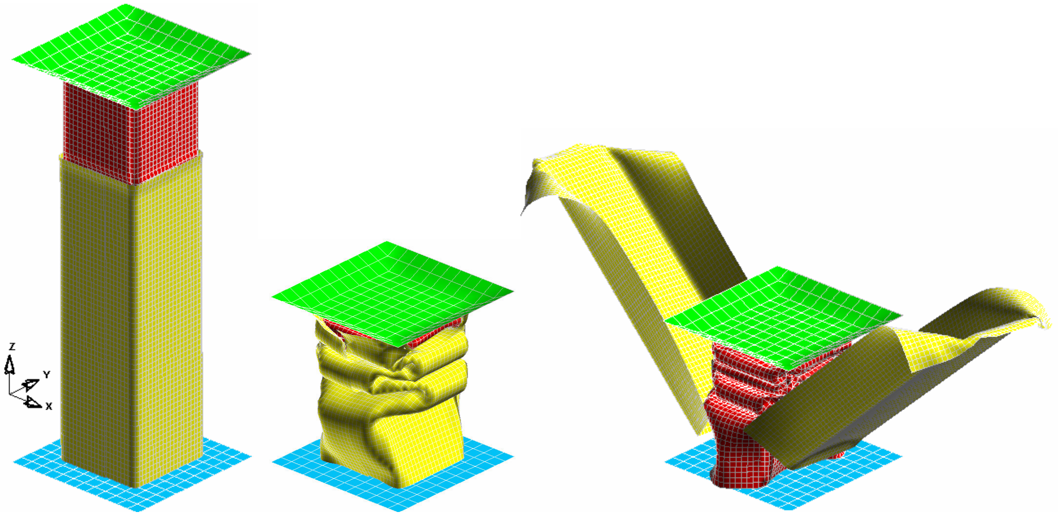

Figure 2. Results of FE simulations (form left): absorber in initial state, passive and active mode

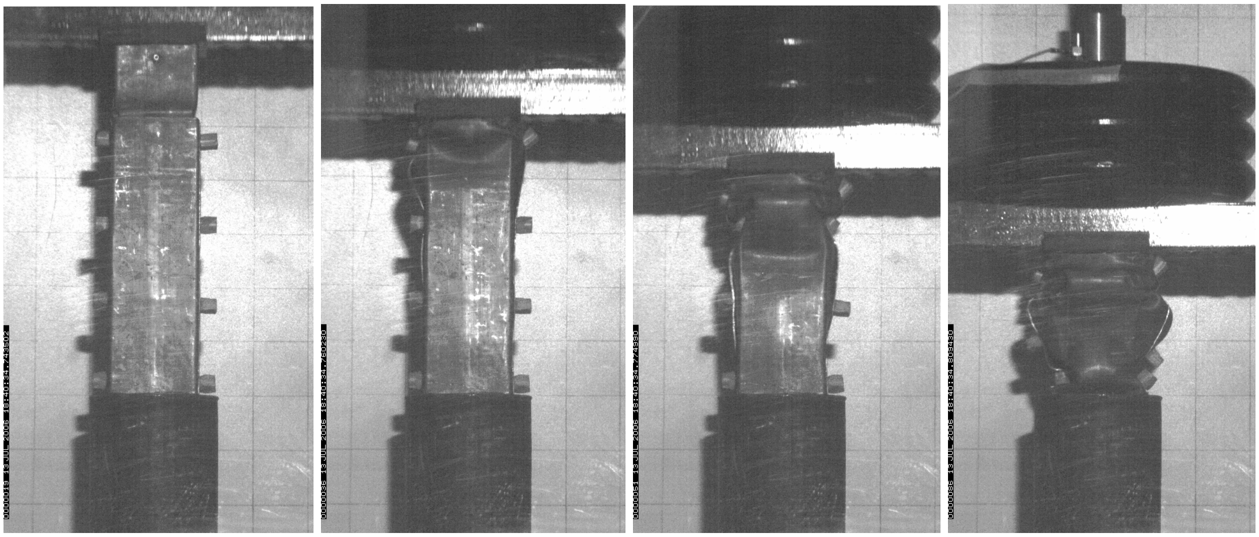

Figure 3. Current results of experimental test – absorber in passive mode (in succession order from left side 0ms,17ms,32ms,67ms)

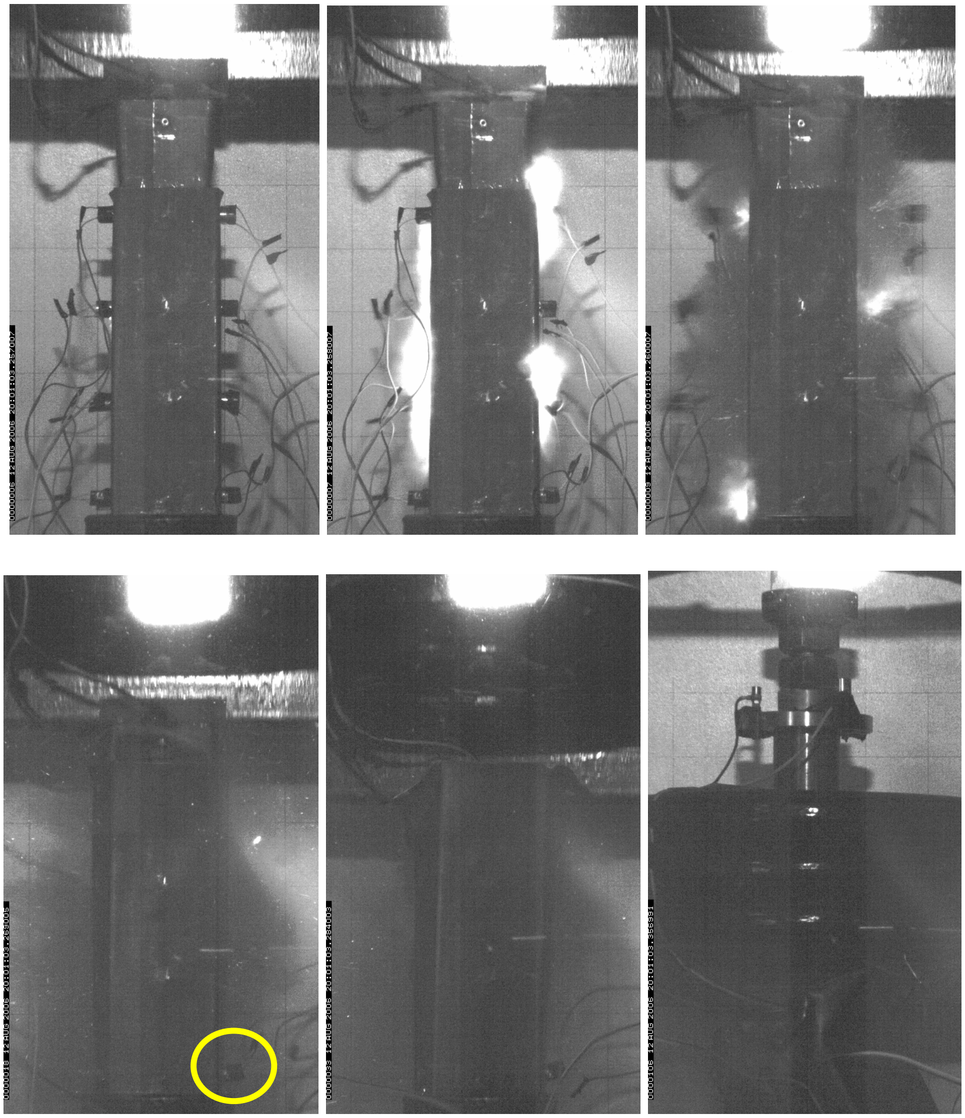

Figure 4. Current results of experimental test – absorber in active mode (in succession order from top left side 0ms,1ms,3ms,12ms,27ms,100ms- remaining pyroconnection was marked)

Experimental research has not been yet not finished and only current, not fully successful results were are presented. High speed camera pictures illustrating the process of inactive mode absorber crush were shown on figure 3. Kinetic energy of the dropping head of the hammer was dissipated through plastic deformations of the absorber. Pictures showing progress of the active mode test were shown in figure 4. First four pyroconnections were activated 1ms after the contact between the head of the hammer and the absorber occurred. The next three ones are fired 2ms later. One lower-right pyroconnection remained closed, however the acting forces broke adjacent material allowing the stiffening members to be disconnected.

A plot of vertical decelerations of the head of the hammer was shown in figure 6 for both inactive and active modes. The deceleration level is distinctly lower for the active mode, however the results cannot be treated as fully valuable due to problems with the remaining pyroconnection mentioned above. A comparison between FE and experimental results is depicted in figure 6, displaying comparable average deceleration levels without full shape conformity.

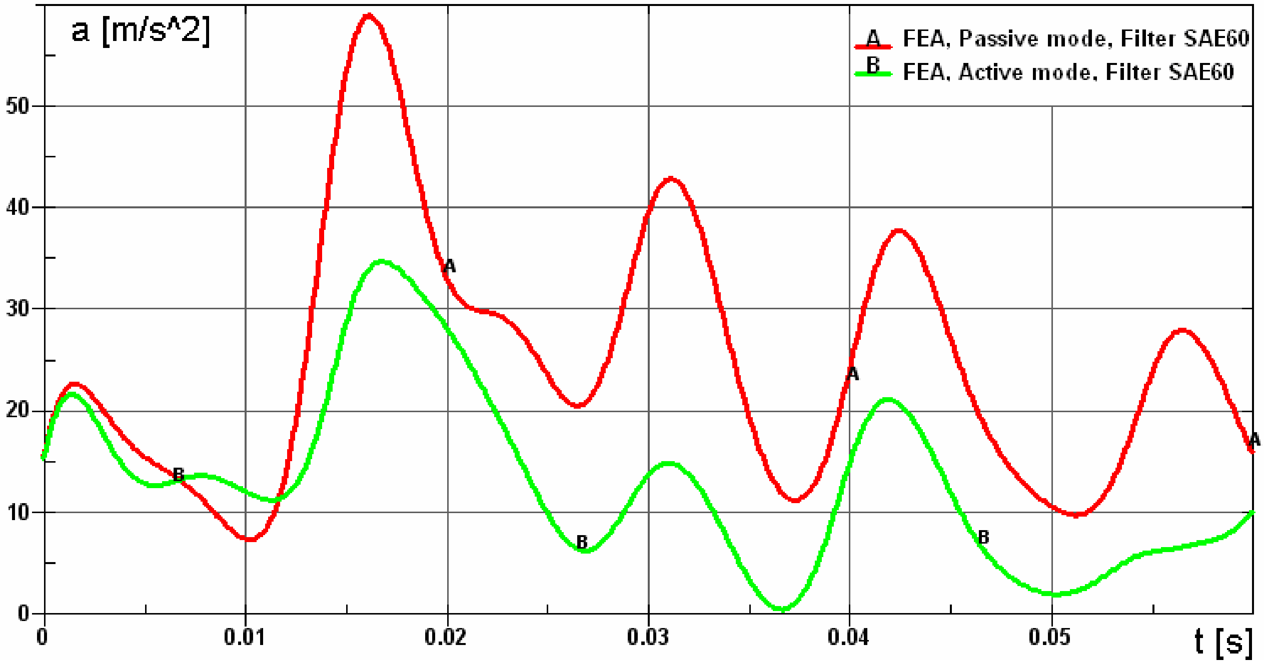

Figure 5. Vertical deceleration of the hammer head as an function of time – comparison between passive and active mode in FE simulations

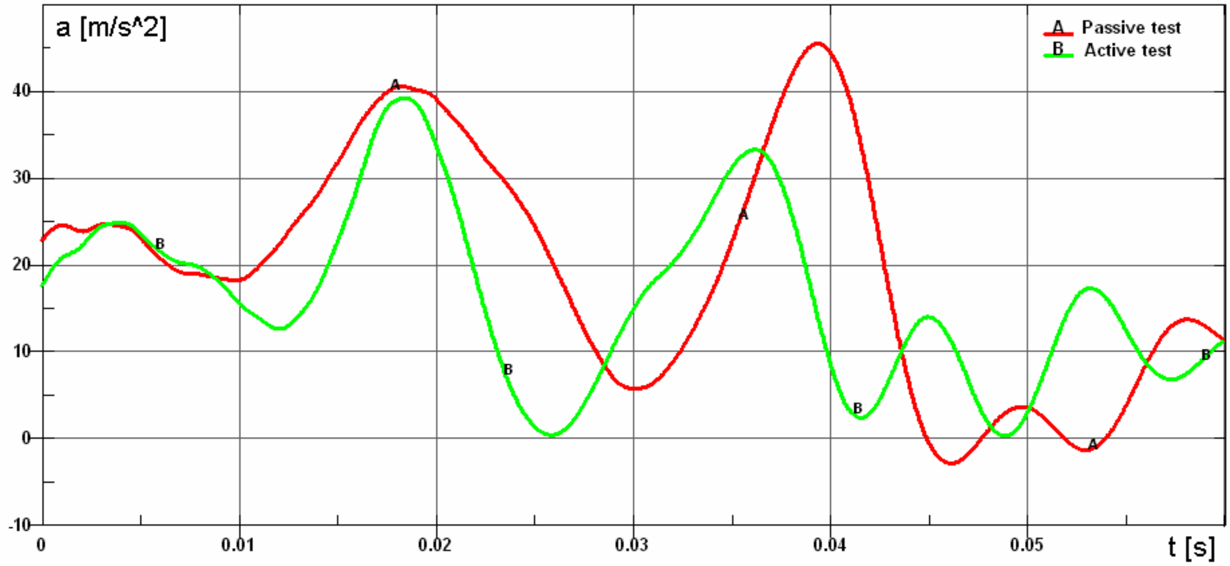

Figure 6. Vertical deceleration of the hammer head as an function of time – comparison between passive and active mode in experiment

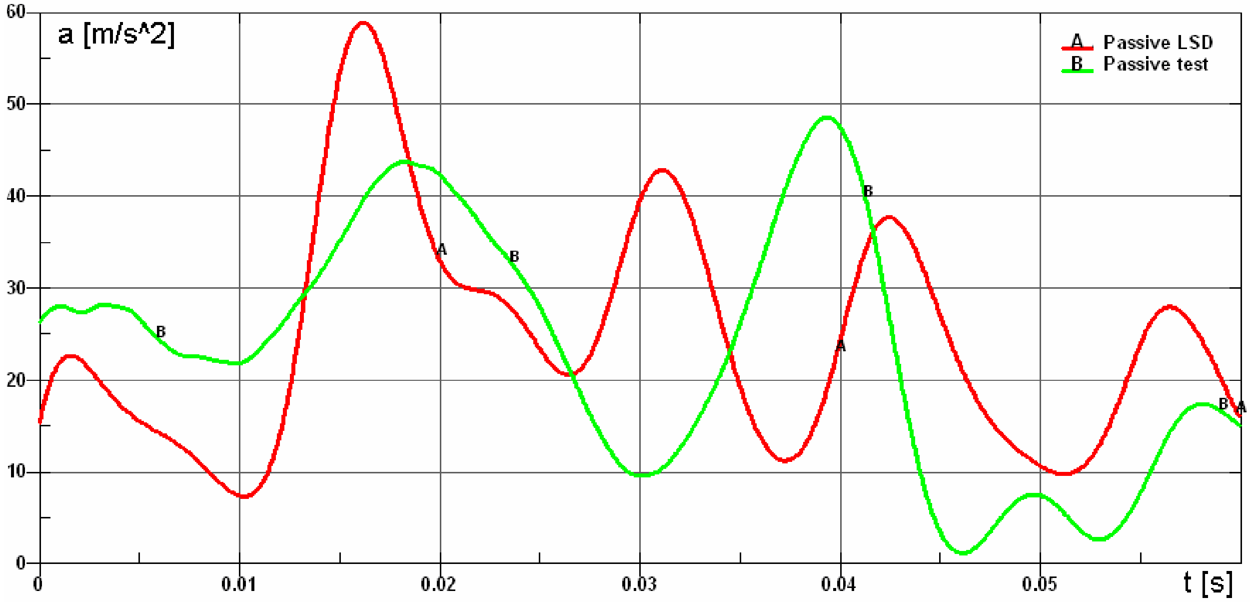

Figure 7. Vertical deceleration of the hammer head as an function of time – comparison of active mode results in FE and experiment

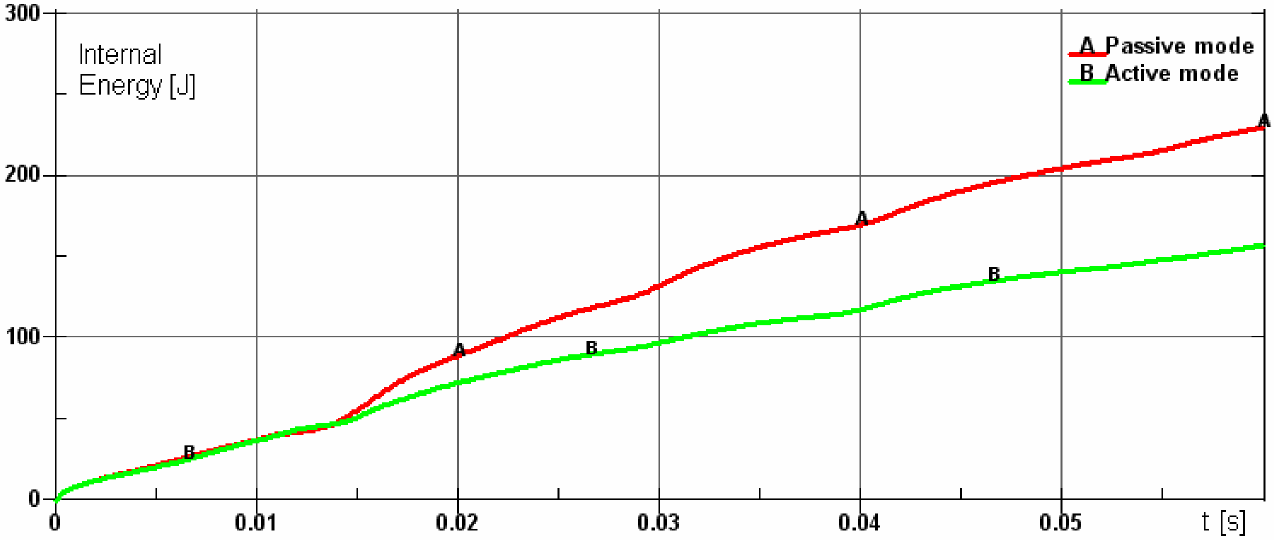

Figure 8. Internal energy plot as an function of time – comparison between passive and active mode in FE simulations

Conclusion

The control of crushing forces in the presented example proved to be possible and efficient. Adaptivity ratio (the energy absorbed in passive mode to the energy absorbed in active mode) achieved in the presented example was 35%. Teh idea of the presented absorber was based on automotive front rail shape, however other possible fields of use seem to be here a perspective. Due to the described problems with explosion time statistics, the experimental tests have to be re-conducted. Also geometry of the tested absorber should be modified to facilitate the detachment process of the stiffening members. Subject of adaptive control of a crash process seems to be prospective for future applications.

Acknowledgement

This research was supported through the Polish Research Project: the *New methods for design of safe structures with identification of hazards and active adaptation in critical states* SAFE-STRUCT, MNiSW 3T11F00930,

References

[1] Ostrowski M., Griskevicius P., Holnicki-Szulc J.. *Feasibility study of an adaptive energy absorbing system for passenger vehicles*. Proceedings of the 16th international conference on „Computer Methods in Mechanics“ Czestochowa, Poland, 2005.

[2] Griskevicius P., Ostrowski M., Holnicki-Szulc J., Ziliukas A. *Crash analysis of adaptive frontal energy absorbers*. Transport Means, Proceedings of the international conference. ISSN 1822-296 X Kaunas: Technologija, 2005, pp. 312-316.

[3] Hallquist, J.O., *LS-DYNA Theory Manual*, Livermore Software Technology Corp., Livermore, 2003.

[4] Wierzbicki T, Abramowicz W. *On the crushing mechanics of thin-walled structures*. Journal of Applied Mechanics,1983, Vol.50,pp. 727-733.

[5] Abramowicz W., Jones N., *Dynamic progressive buckling of circular and square tubes*, Int. J. Impact Eng. 4 1986, pp. 243-270.

[6] Wierzbicki T, Abramowicz W., *The mechanics of deep plastic collapse of thin-walled structures*, in: Structural Failure, Wiley, New York, 1989.

[7] Holnicki J., Mikulowski G., Mroz A., Pawlowski P., *Adaptive Impact Absorption* The Fifth International Conference on Engineering Computational Technology, 2006, Las Palmas de Gran Canaria, Spain.