6th ECCOMAS Conference on Smart Structures and Materials
SMART2013
Politecnico di Torino, 24-26 June 2013
E. Carrera, F. Miglioretti and M. Petrolo (Editors)
www.smart2013.com

SMART, DEPLOYABLE SKELETAL STRUCTURES FOR SAFETY ENGINEERING

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Key words: smart skeletal structures, adaptive impact absorption, safety engineering

Summary. *This contribution presents the concept of smart, deployable skeletal structures along with existing and prospective applications. The first part introduces the concept of multi-folding, which is the basis for the design of all smart deployable skeletal structures. In the second part three diverse innovative applications are described: deployable mobile bridge, adaptive impact absorber and controllable valve.*

1 INTRODUCTION

Safety engineering is a contemporary scientific discipline which focuses on providing safety of humans, structures and systems in case of various unpredictable situations such as damage, collision or environmental impact. The discipline encompasses the problems of load detection and identification, structural health monitoring (SHM) and so-called Adaptive Impact Absorption (AIA) [1].

The adaptive impact absorbing structure is equipped with controlled structural elements that change their mechanical properties in real time. This can be achieved through energy dissipaters (e.g. with yield stresses as control parameters), which trigger plastic-like behaviour in overloaded zones. The pre-determined optimal distribution of plastic-like properties of structural elements, realized by structural fuses in the form of controlled pneumatic or hydraulic valves, can significantly increase the total energy dissipation and improve the overall structural performance. The concept of AIA was validated e.g. in FP6 project ADLAND [2], dedicated to development of adaptive semi-active aircraft landing gear.

Introduction of intelligent materials in the design of the adaptive landing gear allowed for substantial shortening of the system response time and enabled real time control of the damping force generated by the absorber. Within the project two alternative solutions were tested: the magneto-rheological valve based on application of the magneto-rheological fluid and the magnetic head and the valve based on piezoelectric actuator controlling flow of the standard hydraulic fluid. Fig. 1 presents experimental results of optimal control applied to the landing gear in two landing scenarios. It is clearly visible that approximately 15% reduction of peak contact forces can be achieved in a broad range of landing velocities.

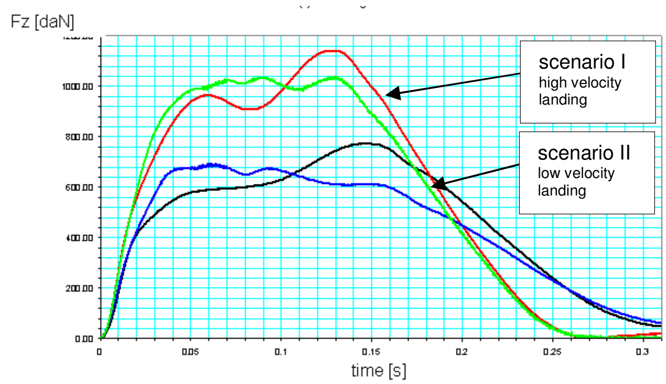

Figure 1: Adaptive aircraft lading gear - FP6 project ADLAND - flight tests, experimental results

2 THE CONCEPT OF MULTI-FOLDING MICROSTRUCTURE (MFM)

The concept of multi-folding defines a basis for the design of a class of further presented smart skeletal structures. This intelligent skeletal structure was introduced and verified numerically and experimentally as energy-absorbing system [3]. The proposed structure is composed of truss-like elements arranged into a special pattern, depicted in fig. 2. Each element is equipped with a micro-fuse which enables control of the actual level of axial force. Appropriate triggering of the micro-fuses allows to provoke various folding sequences (the so called 'multifolding') and to obtain repetitive use of elements providing synergistic effect in the process of energy dissipation.

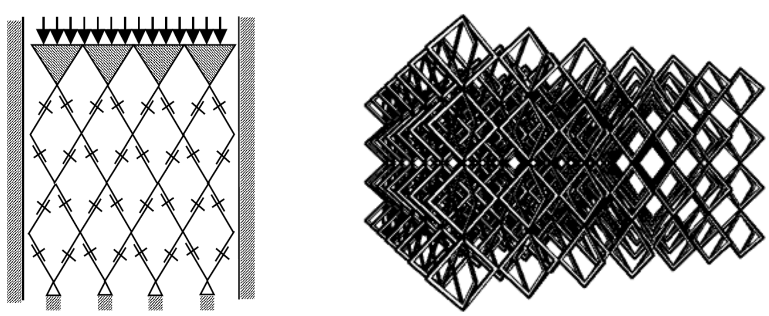

Figure 2: Multifolding structure – general concept

A basic component of the analyzed multi-folding structure is a simple system composed of two straight bars, so called **von Misses truss**. Classically, the structure is composed of two elastic bars located at acute angle to horizontal direction and equipped with pin joints.

Two basic modifications of von Mises truss include: i) change of constitutive equation describing material characteristics of the bars into nonlinear elastic or dissipative, ii) adding point mass and linear dashpot in order to consider the influence of inertia and damping. Herein, elastic, plastic material characteristics followed by general pneumatic model will be analyzed with the use of static and dynamic mechanical simulations.

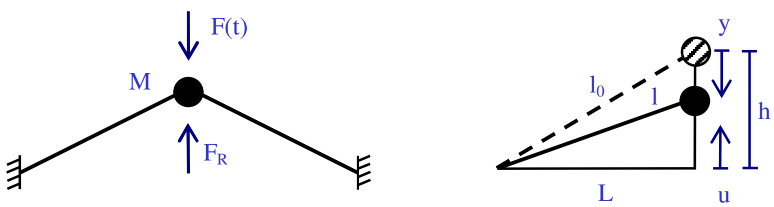

Figure 3: Basic scheme of analyzed von Mises truss

Comparison of static force-displacement characteristics for a linear system, elastic von Mises truss and plastic von Mises truss is presented in fig.4. The plots clearly reveal bi-stable nature of considered two-element truss. In contrast to a linear system, von Mises trusses have more than one equilibrium configuration corresponding to zero external loading.

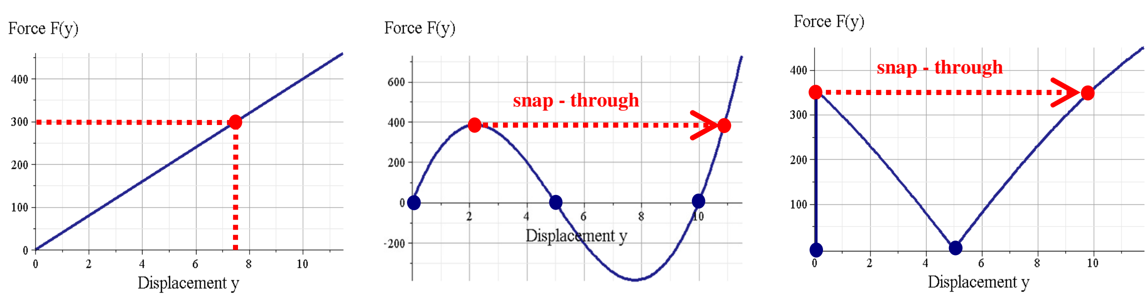

Figure 4: Comparison of dynamic characteristics of 1DOF linear system with elastic and plastic von Mises trusses

In a standard process with gradual change of force the system smoothly follows the equilibrium path. Once the system reaches local extremum of reaction force (a critical point) a snap-through effect occurs. From mechanical point of view this indicates sudden transition between two remote positions of static equilibrium which occurs at infinitesimal change of external load.

Numerical simulations conducted for von Mises trusses composed of elements of both elastic and plastic material characteristics had revealed the following, bifurcational response of the system:

- the occurrence of snap-through effect in both elastic and plastic structure as a result of force excitation,
- the occurrence of snap through-effect in elastic system as a result of unilateral kinematic excitation (start of the phenomenon from horizontal position),
- the lack of snap-through phenomenon in plastic system caused by unilateral kinematic excitation (the reaction force In plastic system does not fall below zero),
- chaotic response of the elastic system in terms of initial conditions (u_0, V_0), as well as in terms of parameters of the system M, C, EA (see Fig. 5a),
- chaotic response of elastic system to harmonic excitation of various frequency or amplitude (Poincare map, Fig. 5b).

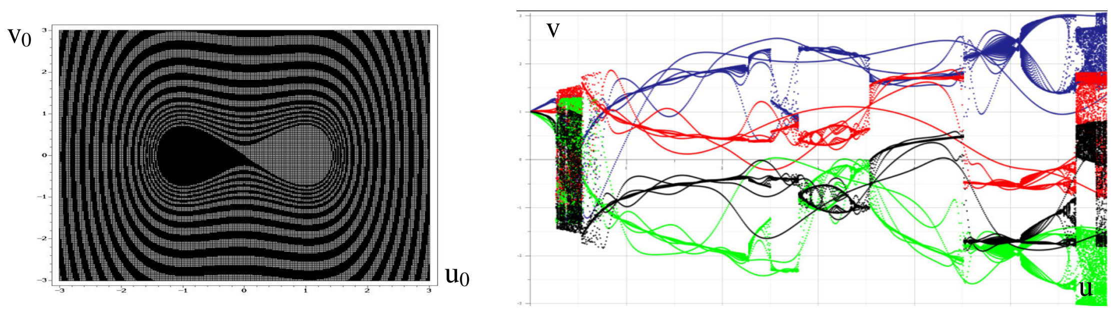

Figure 5: Response of von Mises truss to dynamic excitation: a) final location of mass in terms of initial conditions, b) response to harmonic excitation of various amplitude and phase angle

Beside described above response of passive von Mises truss, the other intrinsic topic required for the design of MFM structures is control of snap-through effect. Both, static and kinematic excitations can be treated as efficient methods of actuation once they are executed in a fully controlled way, e.g. with the use of piezoelectric or magneto-strictive actuators. Such classical types of linear actuators can be replaced by angular actuators mounted at pin-joint at both sides of the truss or by actuation with the use of magnetic field acting on a central mass. In another type of controllable von Mises trusses the control of deformation is not applied by change of external excitation, but by altering properties of the structure. The first possibility is controlling dissipative properties of hydraulic or pneumatic dampers by real-time control of valves opening or change of yield stress level of magneto-rheological damper. The second possibility is replacing pin-joint at both sides of the truss by controllable clutches with controllable dissipative characteristics.

In the following stage of research static and dynamic response of multi-stable skeletal structures constructed as a pile of bistable von Mises trusses (so called **Multi-folding microstructures, MFM**) were investigated. Such construction provides that the structure is multi-stable and may undergo various types of deformation depending on mechanical properties of the particular elements and type and characteristics of the applied loading. The analysis will be conducted subsequently for structures composed of elastic, elasto-plastic and pneumatic elements.

Basic static model of multilevel MFM structure is based on equation, which defines the force of reaction of the system generated by two bars located at the same level. In considered multi-level structure the equations of equilibrium are set for each central and lateral node of the structure. Each equation takes into account forces generated by elements located above and below considered node. Due to the fact that multiple snap-through effects are expected, the equation of equilibrium is complemented with the contact forces arising during collision between the nodes and collision of the nodes and the supports. Three basic models of MFM structures can be distinguished:

- static model where the system of equations involving static internal and external forces is solved (system of nonlinear algebraic equations),
- quasi-static model which additionally takes into account damping forces (first order system of differential equations),
- dynamic model, which additionally takes into account inertial forces resulting from mass of the elements located at nodes modelling in simplified manner inertia of the elements (second order system of differential equations).

Numerical simulations of the multi-folding process were conducted with the use of various mathematical models and various types of excitations. In all considered cases it appeared that the response of the system is bifurcational and multiple folding of bar elements located at subsequent levels of the structure occurs.

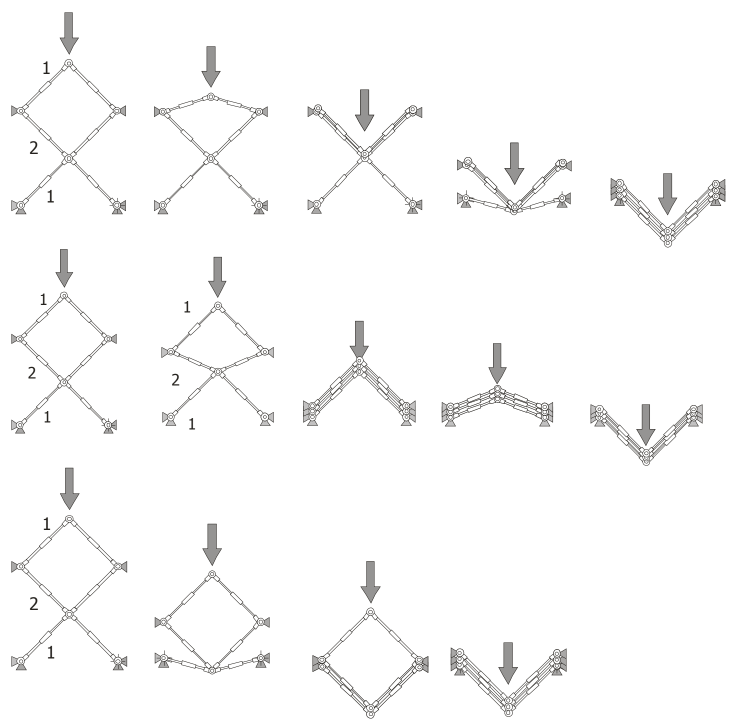

Figure 6: Folding modes for the basic multi-folding structure

The simulations had revealed high sensitivity of the MFM structure on geometrical parameters and stiffness of the bars, as well as high sensitivity on the type of applied excitation. Nevertheless, certain qualification of the above chaotic behaviour can be proposed. Exemplary for the multi-folding structure composed of three levels of bar elements three basic folding modes (c.f. fig. 6) can be distinguished:

- mode 1: folding of the upper bars followed by folding of the lower bars,
- mode 2: folding of the bars in the middle of the structure followed by simultaneous folding of all bars,
- mode 3: folding of the lower bars followed by folding of the upper bars.

All above described modes of deformation characterize dynamical model of the system, however they can not be always achieved when static or quasi-static model of the system is applied. Therefore, conducted analysis reveals that introduction of damping and inertia terms causes not only smoothing of the structure response, but also increases the variety of potential folding modes.

Although all abovementioned deformation modes can be achieved for different constitutive characteristics of elements, the corresponding equilibrium paths may significantly differ from each other. Fig. 7 presents exemplary force-displacement curve for deformation in mode 1 of elastic MFM structure [4-5]. For kinematic excitation the system has a complex equilibrium path starting at the hill-top bifurcation point BP and following points b–c–d–e–f–g–h. Force control of the load results in two snap-throughs BP-e-h.

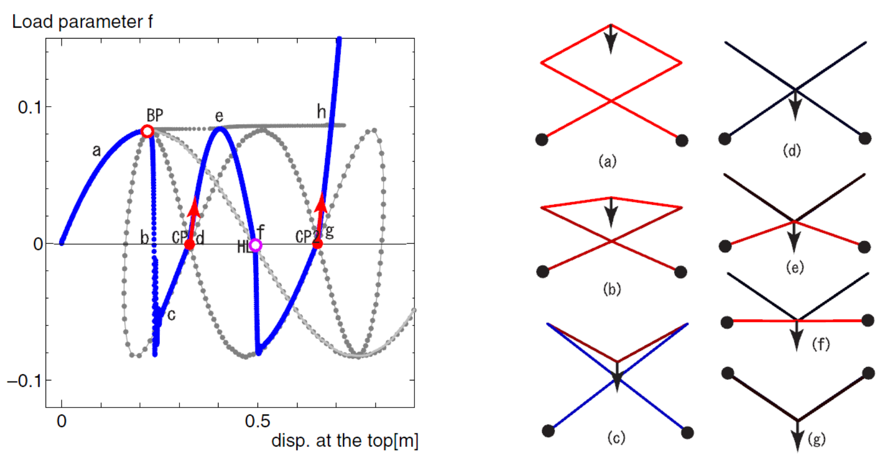

Figure 7: Equilibrium paths for the mode 1 of elastic multi-folding structure

Analogous modes of deformation can be obtained for the multi-folding structures with elasto-plastic and rigid-plastic characteristics of elements. In this case the sequence of subsequent local collapses is triggered by distribution of yield stresses in layers of the structure. Fig.8 depicts exemplary deformation mode and corresponding equilibrium curves of multi-folding structure composed of five levels of elements.

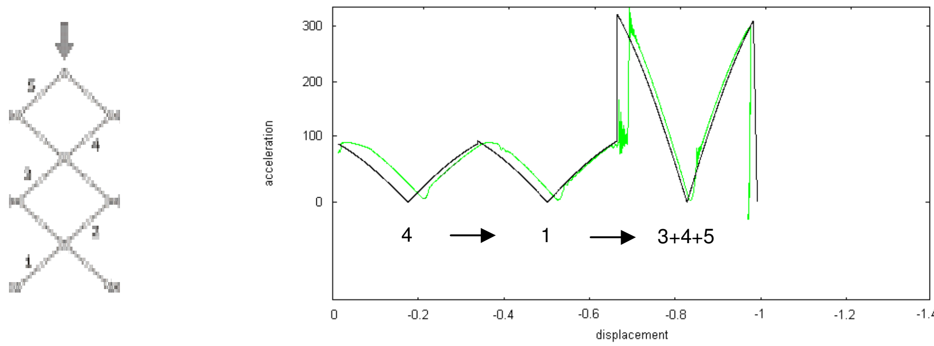

Figure 8: Plastic multi-folding structure composed of five layers of elements

Current research in the field of multi-folding structures focuses on development of various smart technologies for the design of adaptive truss-like elements. In this paper we propose application of pneumatic cylinders equipped with controllable valves which allow for smooth change between elastic and dissipative characteristics and, as a result, for precise control of the folding process. The above features were confirmed by numerical simulations of the pneumatic system subjected to kinematic and static excitation (Fig. 9).

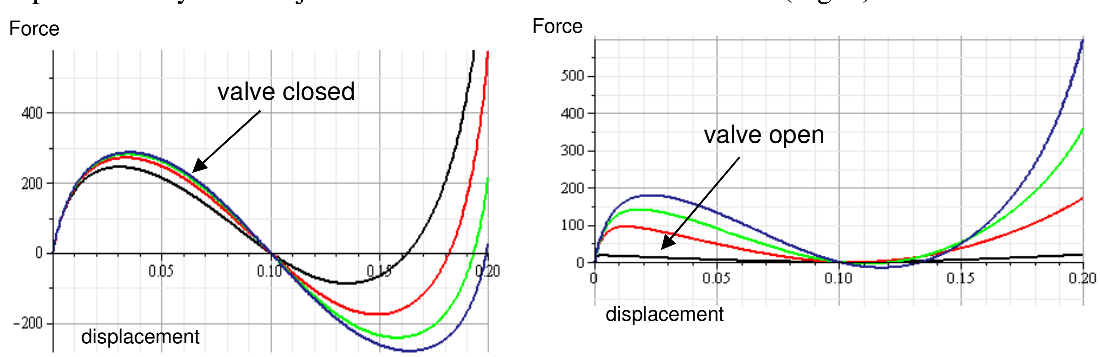

Figure 9: Force-displacement characteristics of pneumatic von Mises truss for different opening of the valve

Deriving mathematical models of pneumatic MFM structures is substantially more complex than in case of elastic or plastic structures. The aim of the constitutive modelling is to determine force generated by the absorber in terms of in terms kinematics of piston movement and valve opening. Determination of gas parameters requires considering energy conservation laws for both chambers involving gas internal energy, global work done by gas, energy transferred to the system in the form of heat, and enthalpy of added/removed gas.

The second step of the derivation of the model of pneumatic MFM system is assembling geometrically nonlinear equilibrium equations for pneumatic von Mises truss. Exemplary results obtained for the basic multi-folding structure are presented in fig. 10.

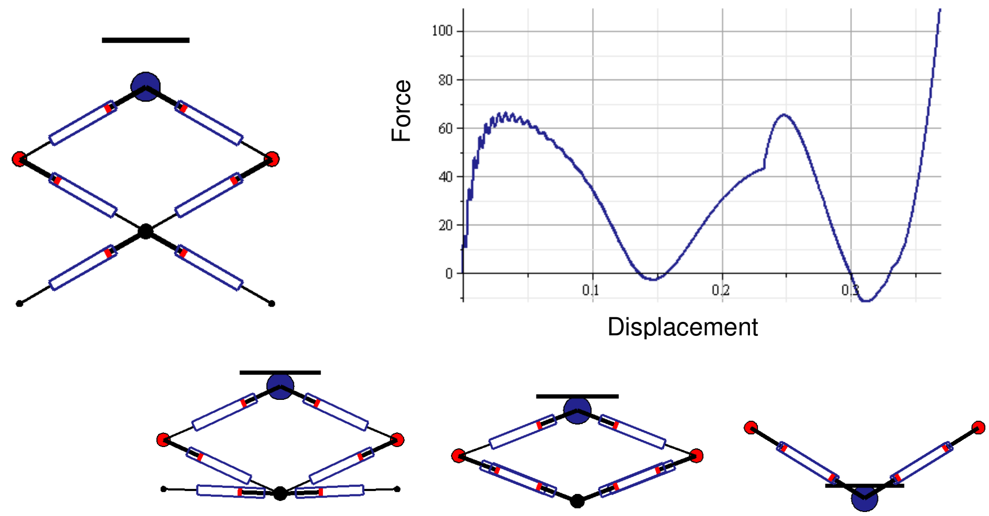

Figure 10: Force-displacement characteristics of pneumatic MFM structure

3 APPLICATIONS OF SMART DEPLOYABLE SKELETAL STRUCTURES

Skeletal structures composed of plastic multi-folding can be efficiently used as adaptive absorbers of dynamic loads. Control strategy based on optimal distribution of yield stresses in horizontal layers of element provides significant reduction of peak impact forces.

Application of MFM structure as adaptive barrier is shown fig. 11, which describes dependency of maximal peak acceleration of the loaded node on kinetic energy of the load. High acceleration occurring with passive system can be significantly reduced by the use of optimal control. Increased number of layers of the structure provides further gain of system's efficiency.

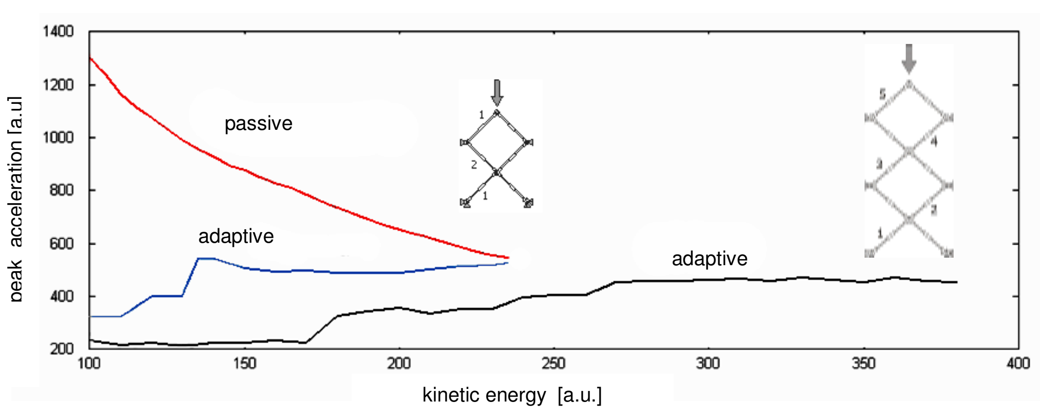

Figure 11: Comparison of the efficiency passive and adaptive multilayered MFM absorbers

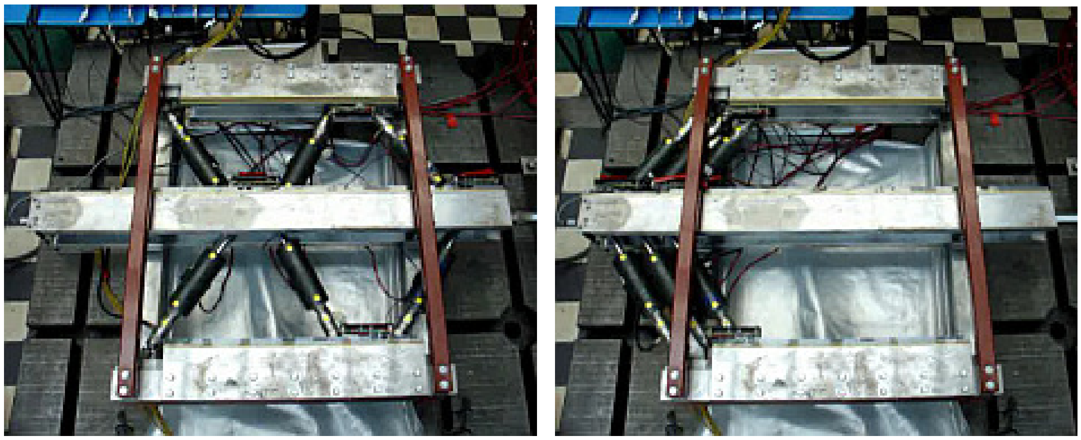

Figure 12: Experimental verification of MFM mechanism

Experimental set-up depicted in fig. 12 was developed in order to validate the concept of multifolding. The analysed system was composed of six magnetorheological fluid dampers RD-1005 with damping characteristics controlled by magnetic field. Application of proper control signals allowed to obtain all basic deformation modes.

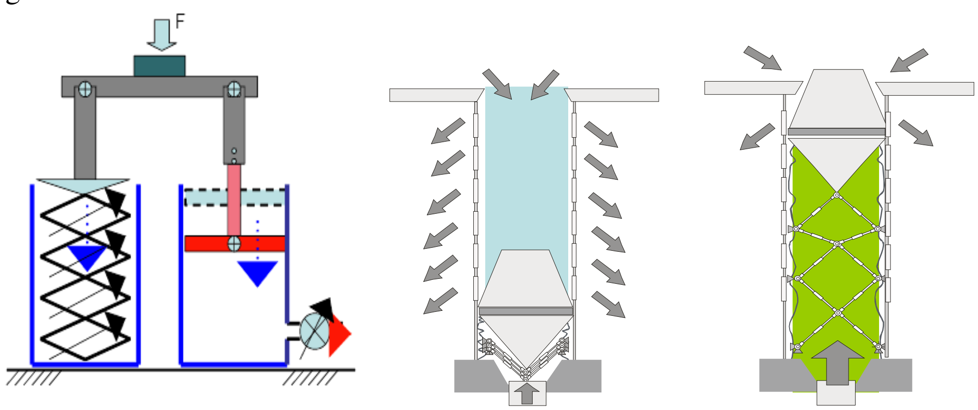

Figure 13: MFM-based pneumatic shock absorber (a), MFM-based high stroke valve

Multifolding structures can be also implemented as a part of pneumatic or hydraulic shock absorbing devices. Fig. 13a presents improved design of the basic MFM absorber, combining subsequent folding deformations with controllable compression of fluid contained in a cylinder. Another field of application is related to adaptive inflatable structures [6], which require controlled release of pressure during impact. Fig. 13b depicts a high-stroke MFM-based valve allowing for fast release of pressure and further blocking of the flow caused by additional gas generator

Figure 14: Applications of multifolding: to a mobile bridge

One of the successful applications of the concept of deployable skeletal structures is a mobile bridge (fig.14). Although the concept is not directly related to the problem of adaptive impact absorption it effectively utilizes the mechanism of folding and beneficial distribution of internal forces in structures of a multifolding shape. The bridge is composed of scissors-like structure which can be easily transported and deployed for the use in case of emergency or natural disaster.

ACKNOWLEDGMENT

This project was financed from the funds of the National Science Centre (Poland) allocated on the basis of the decision number DEC- 2012/05/B/ST8/02971. Financial support of Structural Funds in the Operational Programme - Innovative Economy (IE OP) financed from the European Regional Development Fund - Project "Modern material technologies in aerospace industry", Nr POIG.01.01.02-00-015/08-00 is gratefully acknowledged.

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