

ADAPTIVE IMPACT ABSORPTION - THE CONCEPT, SIMULATIONS AND POTENTIAL APPLICATIONS

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Abstract. *Adaptive Impact Absorption focuses on adaptation of energy absorbing structures to actual dynamic loading by using system of sensors detecting and identifying impact in advance and semi-active dissipaters with controllable mechanical properties which enable change of system dynamic characteristics in real time. The article presents a review of research conducted at the Department of Intelligent Technologies of the Institute of Fundamental Technological Research dedicated to applications of systems for Adaptive Impact Absorption. Wide range of presented examples covers pneumatic landing gears, bumpers for offshore towers, wind turbine blade-hub connections and protective barriers for automotive applications.*

1 INTRODUCTION

The motivation for undertaking research in the field of Adaptive Impact Absorption is development of alternative, efficient and robust systems for impact energy dissipation which are required in many branches of contemporary engineering. The impact loading under consideration may be of various source and nature: it may be service loading resulting from typical destination of the structure (airplane landing gear), it may occur during emergency situation (ship hitting the offshore tower) or it may be caused by harsh environmental conditions (hurricane or earthquake). Independently on type of impact loading optimal dissipation of the corresponding impact energy constitutes one of the fundamental problems from the point of view of safety and economy. Application of incorrect or non-optimal solutions inevitably leads to serious damages of impacting objects, resulting threat to life or health or high material costs. Structures currently applied for impact energy dissipation are usually passive systems which are designed for the typical expected or maximal allowable impact energy. However, in many practical cases the characteristics of the impact loading acting on the structure may vary significantly or it may be difficult to evaluate precisely. Therefore, most of the classical passive energy absorbing structures do not provide optimal protection against wide range of possible impact scenarios.

Recently, the innovative concept of Adaptive Impact Absorption (AIA) which overcomes the disadvantages of passive systems is comprehensively developed by our research group. The essence of AIA is real-time adaptation of energy absorbing structures to actual dynamic loading aimed at improvement of the dissipation process and optimal mitigation of the structural

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response^{1,2,3}. Adaptive impact absorbing structures utilize systems of sensors to detect and identify impact in advance⁴ and controllable dissipaters (structural fuses) to adjust dynamic characteristics of the system during the impact process. The adaptation is executed in a semi-active way, i.e. exclusively with the use of controllable dissipaters, where the task for actuators is reduced to modification of local mechanical properties and the need for external energy sources is minimized. Application of the above paradigm allows for substantial improvement of global dissipative properties of the structure without significant increase of weight and external energy demand.

Various strategies of adaptation to identified impact scenario can be proposed depending on the particular problem under consideration, e.g. repetitive exploitive loads vs. critical emergency impact. Minimization of accelerations values in the selected locations for smoothing down the impact reception corresponds to the first case, when reduction of fatigue accumulation is an important issue. On the other hand, maximization of the impact energy dissipation in the selected time interval for the most effective adaptation to the emergency situation corresponds to the second case. In general, the AIA system should be designed for random impact multi-loads, which creates new research challenges related to optimal forming of structural geometry and optimal location of structural fuses.

Nowadays, the design and practical realization of AIA systems is possible and justified due to a broad accessibility and low cost of functional materials and required electronic devices (sensors, actuators and hardware controllers). Adaptive impact absorbing structures can be based on miscellaneous adaptation techniques such as application of magneto-rheological fluids, piezoelectric valves controlling flow of the medium or detachable pyrotechnic connections. However, each of the above solutions has its disadvantages, e.g. long response times or insufficient controllability, which confine the range of their possible applications. Therefore, an additional challenge in AIA is selection of appropriate technology and design of the controllable dissipative devices which will allow for adaptation to impact loading in particular practical application. As it will be discussed in the paper, adaptive pneumatic shock absorbers based on piezoelectric valves can be successfully utilized as adaptive landing gears which optimally mitigate the process of landing. On the other hand, dissipaters based of shape memory alloys (SMA) can be applied as structural fuses in adaptive bumpers protecting offshore towers against impacts. Moreover, as it will be proved, magneto-rheological clutch used as adaptive connection between hub and blade of the wind turbine allows for mitigation of strong wind gusts. Finally, the concept of real-time adaptation by control of internal pressure inside multi-chamber thin-walled structure will be used for design of adaptive road barrier.

The objective of this paper is to present the concept of Adaptive Impact Absorption by using several examples from various branches of engineering. The paper presents an overview of research in the field of AIA conducted recently in our group. All applications are presented in a nutshell. More detailed description of the particular solutions can be found in previously published conference and journal papers, as well as in doctoral theses of the authors.^{5,6,7}

2 PNEUMATIC ABSORBER EQUIPPED WITH THE PIEZOELECTRIC VALVE

One of the concepts of pneumatic impact energy absorbers for protection of impacting object, involved the utilizing of a piezoelectric valve⁸. In the structure of the proposed system the piezoelectric valve is placed inside the piston that moves in the cylinder during a collision (Fig. 2.1).



Figure 2.1: Schematic of the pneumatic impact energy absorber with the reaction force value control circuit (left) and the disassembled absorber (right)

The reaction force in this kind of impact energy absorber is adjusted via the mass flow rate control of the gas migrating between two spaces inside the cylinder on both sides of the piston. The mass exchange takes place thanks to the presence of the valve inside the piston. The investigated piezoelectric valve utilized in the absorber is shown in simplified cross-sectional scheme in Fig. 2.2.

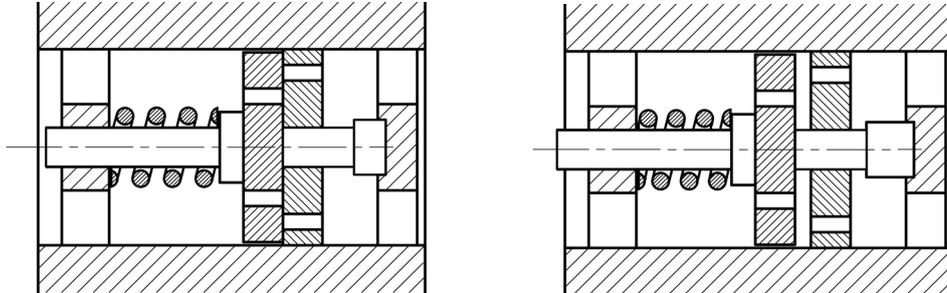


Figure 2.2: Main elements of the valve when it is closed (left) and opened (right)

The valve consists of two Hörbiger plates with through holes. When the valve is closed, the plates are aligned mutually and the holes of both plates do not overlap. The valve opening is achieved by the piezo-actuator's elongation that results in moving one plate apart from the other one. In the latter situation the gas can flow in the space between the plates. During the contraction of the actuator one of the plates, which is mobile, is moved back toward the immobile one by the spring (marked on the right-hand side in the cross-section view – Fig. 2.2) and closes the valve.

The desired force path realized via the absorber during the impact phenomenon consists of two stages. During the initial period of the impact the piston is moved with the closed valve and the gas is compressed. After the reaction force reaches the required level it is required to be constant. The held value is on the level by which the whole admissible stroke of the piston inside the cylinder is utilized (Fig. 2.3.) during the energy absorption process. That can be achieved by appropriate opening and closing the valve. Realization of such a strategy on the absorber, leads to the minimization of the maximal values of the reaction force and therefore to protecting the structure against unfavorable overloads.

Because of the fact that the mass flow rates of the gas flowing through the valve are finite, there is a maximum piston velocity for which the strategy depicted in Fig. 2.3 is feasible. The value of this critical velocity depends on the absorber's geometry as well as on the maximal value of the gas mass flow rates.

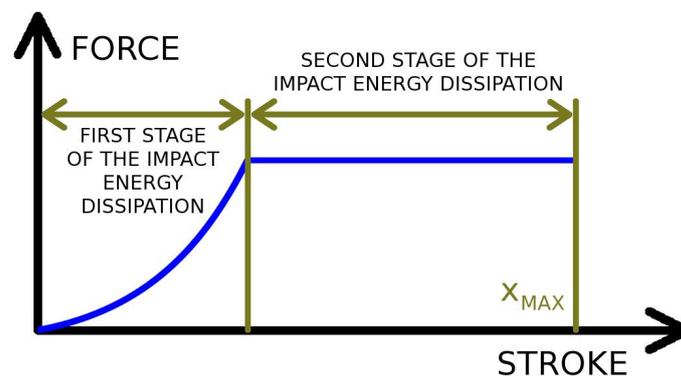


Figure 2.3: Force dependency in the function of the absorber deflection. The reaction force is controlled to hold its value on the predefined level.

To determine the particular range of the impact velocities within which the adaptive strategy (shown in Fig. 2.3) can be realized, a series of experiments on the valve was carried on in order to measure its characteristics. The applied set-up consisted of the housing with the investigated valve, two containers, pressure transducers p_0 , p_1 , p_2 , temperature transducers T_0 , T_1 , T_2 , and the pressure regulator (Fig. 2.4).

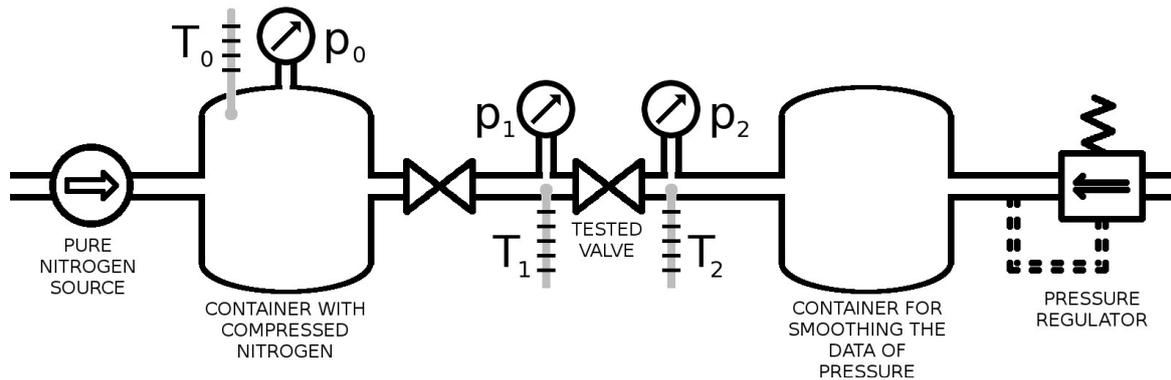


Figure 2.4: Schematic of the stand used for the valve investigation.

In each test the gas flow from the container symbolically marked on the left hand side in Fig. 2.4. to the container drawn on the right hand side in this schematic view. The mass of the gas inside the left container (that is connected to the valve inlet) in the subsequent time instants was determined by the measurement of the ram pressure and the total temperature in this container. By means of these mass values the mass flow rates were obtained (this method is similar to the one applied by Iwaszko in the investigation of the gas flows through throttling elements⁹). Conditions present at the valve inlet and outlet were acquired thanks to the application of the transducers p_1 , p_2 , T_1 and T_2 . The pressure regulator served for keeping pressure value in the second container on the constant level. An exemplary 3D-plot illustrating the valve properties by various inlet and outlet pressures is shown in Fig. 2.5. These results concern the 80 μm spacing between the Hörbiger plates. The stream cross-section in this place is equal to 7.5 mm^2 and is minimal for the whole flow.

Approximate calculation gives the result that the impact energy absorber having inner cylinder diameter equal to 32 mm and the piston stroke of 100 mm is able to work efficiently when the kinetic energy of impacting object does not exceed 50 J and the collision velocity is not higher than 2.5 m/s.

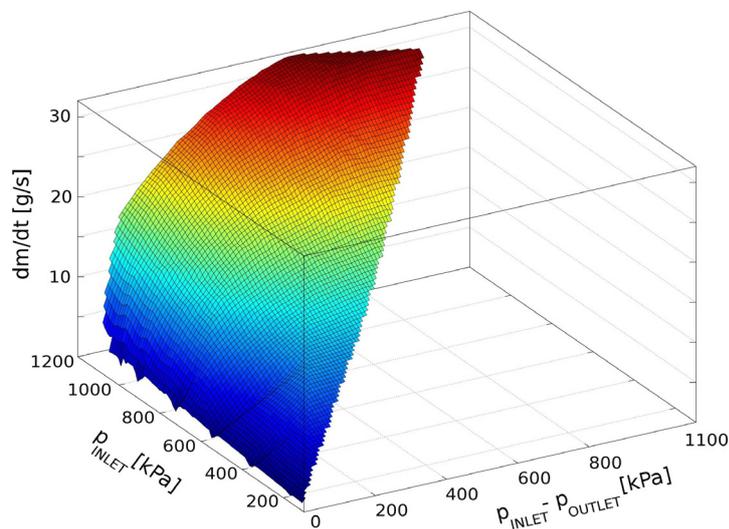


Figure 2.5: Mass flow rate dependency. On the horizontal axes are values of the pressure at the valve inlet and pressure difference between the inlet and outlet of the valve

This absorber behaviour prediction is consistent with the results obtained in the experiments carried on with the drop test stand - a system having vertical rail guideline with the vehicle having linear planar bearings (Fig. 2.6a). In Fig. 2.6b is illustrated the comparison between the collision by which the absorber valve was instantly closed (passive case) with the collision with active valve control circuit (Fig. 2.1.). The impact energy was equal to 8.3 J while the initial velocity was 1.4 m/s.

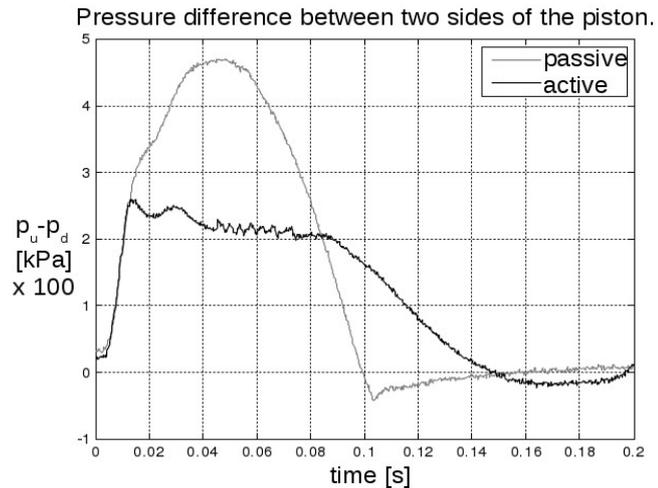


Figure 2.6: a) Impact energy absorber on the drop test stand
 b) Pressure difference for both sides of the piston inside the absorber cylinder in the function of time. In the passive case the valve was closed during the whole impact; in active case the valve was controlled to keep constant pressure difference on both sides of the piston

Presented results reveal that the chosen concept of the valve structure is appropriate to implement it in adaptive impact energy absorbers. In particular, piezoelectric actuators can be applied in the valves to efficient control of the gas migration. The potential application do have to be analyzed in order to determine the allowable operating temperature range and fatigue requirements in order to adjust them with the properties of the utilized piezoelectric material.

3 ADAPTIVE WIND TURBINE BLADE

3.1 Introduction

In order to meet the EU goal for the wind energy production for year 2020 it is expected that the rate of the market growth will be increasing, and considering that one big wind turbine is more efficient than many small ones, it is expected that also the size of wind turbines continues to increase. There are, however technological barriers on the way to up-scaling of wind turbines, such as the blade weight limit, blade tip linear speed limit and the blade critical loading. Classical control mechanisms may be adapted for load reduction control strategies, as described in^{10,11,12} even though their main task is to maximize the energy capture.

In particular the blade root bending due to extreme wind gusts causes the blade root bending stress to be a design limiting factor. Two possibilities to overcome this barrier are the new composite materials development on one hand and new adaptive solutions on the other. The latter is the subject of presented work.

3.2 Concept of extreme gust loading alleviation

A semi-active adaptation technique was proposed basing on the following observation. Since the aerodynamic torsional moment forces a blade to turn to feather, it can be expected that, once the torsional connection of a blade is freed, it could increase the blade pitch angle thus reducing the blade loads caused by a gust. Consequently the root bending and resulting stresses could be also mitigated¹³.

For the purpose of assessing the effectiveness of the proposed solution a simple wind turbine numerical model has been built. The turbine chosen for simulations was similar to a 5 MW, variable speed, pitch regulated turbine analyzed by Lindenburg¹⁴. The model consists of aerodynamic, structural and adaptation modules. All degrees of freedom that influence the aerodynamic forces are included in the model. Control procedures can be applied to any degree of freedom. Detailed numerical study is available in¹⁵.

The adaptation process is activated upon the detection of an extreme wind gust. Wind gusts implemented in simulations take the deterministic form according to the international standard¹⁶ (Fig. 3.1a).

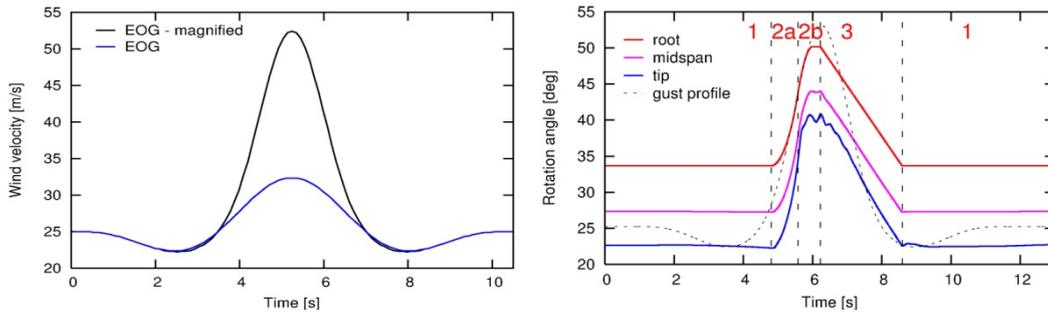


Figure 3.1: a) Extreme Operating Gust (EOG); b) Pitch angle changes with control phases

The adaptation of the blade – hub connection is summarized on Fig.3.1b in terms of the pitch angle changes. After the gust detection (1) the blade is unclutched and rotates freely about its axis (2a) until the braking process (2b) is activated. The blade rotation is then slowed down and stopped with a braking system. Once the gust is gone, the initial pitch angle is restored with the typical pitch control mechanism (3). Classical pitch control mechanisms are described f.e. in ¹⁷.

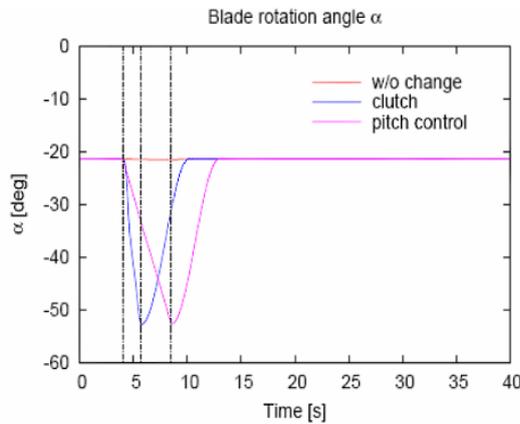


Figure 3.2: Semi-active vs active device response

The adaptation process described above was compared with a pitching mechanism working with the speed of 6 deg/s. It is observed that the unclutching process (semi-active), with the average rate of ca. 26 deg/s, is faster than the pitching mechanism (active solution), cf. Fig.3.2.

The more sudden the gust, the faster the semi-active solution as compared to the pitching mechanism. Fast reaction time creates a possibility to effectively reduce the internal forces accompanying the rise of an EOG. This, in turn, could be crucial in the wind turbine up-scaling process as the blade root bending is an important design criterion. On the other hand blade rotation cannot be too fast as it may cause an excessive rebound in the blade and tower response, cf. Fig.3.3. It is therefore crucial to control the process of blade rotation driven by the unbalanced aerodynamic torsional moment. An example answer, i.e. tower and blade bending are depicted on Fig.3.3a and Fig.3.3b respectively. Results are relative to the steady state responses.

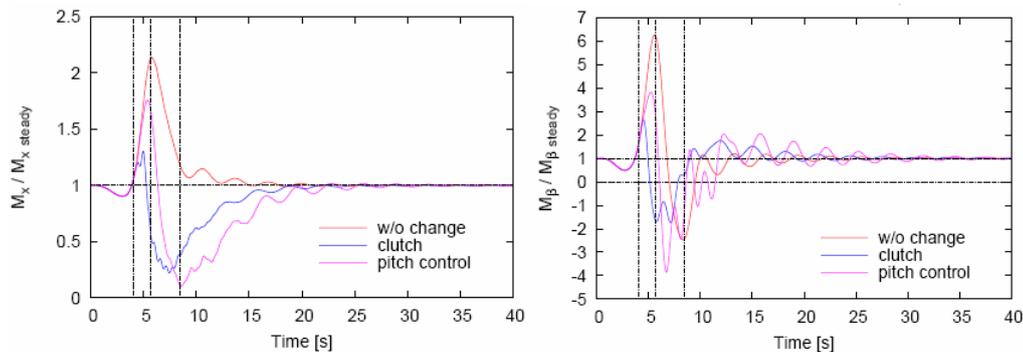


Figure 3.3: a) Tower bending moment, b) Blade bending moment

3.3 Experimental demonstration

Experiments in open jet wind tunnel have been carried out to demonstrate the above load alleviation technique on a two-meter diameter rotor (cf. Figure 3.4). Releasing of the torsional connection between blade and hub has been realized by means of an MRF-based clutch inserted between the blade root and the hub. The general view of the adaptive device is depicted in Figure 3.5.



Figure 3.4. Experimental set-up in wind tunnel.

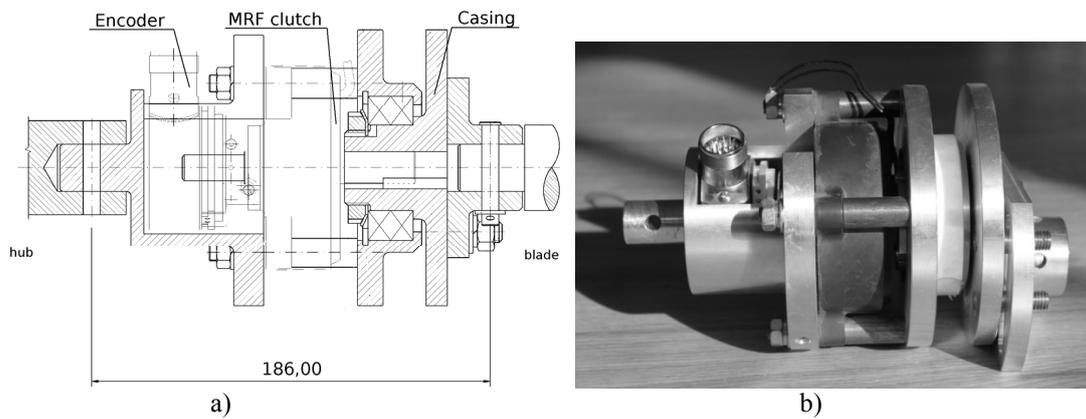


Figure 3.5. Adaptive clutch a) cross section; b) general view

The reaction moments at the blade root, calculated from the strain gauges measurements, change in response to the blade rotation, which is shown in Figure 3.6, for the rotor speed of 180 RPM. Depending on the rotor speed the average value of out-of-plane bending moment (M_{flap}) is decreased 18-29%, as compared with average value before clutch release. Respectively the average values of the in-plane bending moment (M_{edge}) are decreased 54-84%.

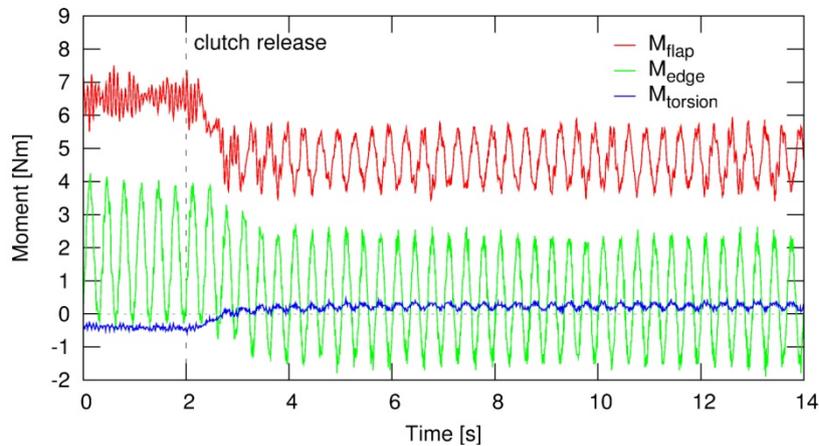


Figure 3.6. Reaction moments at root; rotor speed 180RPM.

3.4 Conclusions

Conclusions from the carried out numerical simulations and experiments are as follows:

- ❖ The proposed semi-active solution could effectively mitigate the internal forces caused by extreme wind gusts, in particular the blade root bending moment
- ❖ A blade can be drawn towards feather by the torsional moment provided that a certain mechanism releases the torsional connection between blade and hub
- ❖ The proposed semi-active solution is faster than the regular pitching mechanisms
- ❖ Blade unclutching system could be considered as an ‘emergency pitch’, in order to alleviate the extreme wind loading.

4 ADAPTIVE TRUSS STRUCTURES

4.1 Introduction

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 very often be fatal for a structure, therefore adaptive truss structures with high impact energy absorption can be effectively applied in shock-absorbing systems. The concept of adaptive skeletal structures was introduced e.g. in publications¹⁸ or¹⁹.

In case of adaptive truss structures optimal energy absorption can be achieved by predesigning the distribution of yield stress levels in active elements located in selected zones of the structure (c.f. Fig. 4.2). Active elements are equipped with devices (so-called “structural fuses”) which control the axial yield forces P in each element.

Fig.4.1 presents a concept of the fuse²⁰, 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 different number of washers. The initial value P_3 (without any activation) can be gradually decreased to P_2 and P_1 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.

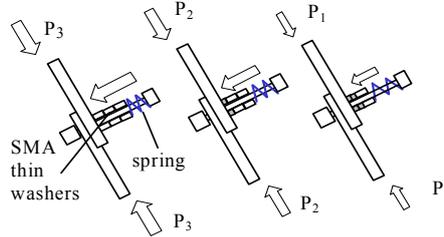


Figure 4.1: The controllable structural fuse

The initial distribution of the control thresholds plays a crucial role in the adjustment of the stiffness characteristics of the structure to the impact loading. Different initial distributions of those parameters will result in different deformation sequences and therefore will change the capability of energy absorption and the level of acceleration during the impact.

4.2 Structural control

Problem of control can be formulated in the following way: for the assumed structure A and for the set of its active elements $E_i \in A$, the optimal distribution of yield stresses must be found, which minimises the objective function f , defined by the index I :

$$\min f(\sigma_i): f \rightarrow I \quad (1)$$

Form of the index I depends on the analysed problem and in the presented case is assumed as:

$$I_1 = \frac{1}{TN^{ctr}} \sum_{t=1}^T \sum_{i=1}^{N^{ctr}} |\ddot{q}_i^{ctr}(t)| \quad (2)$$

$$I_2 = \max_{t,i} \{|\ddot{q}_i^{ctr}(t)|\} \quad (3)$$

where: T – number of time steps, N – number of degrees of freedom, N_{cntr} – number of controlled degrees of freedom, for which acceleration is minimised, $\ddot{q}_i^{\text{cntr}}(t)$ - acceleration of a controlled degree of freedom i at time instance t .

Index I_1 provides information about averaged acceleration of selected control degrees of freedom, which are used in the optimisation procedure. Index I_2 describes peak acceleration values, which occurred in the set of control degrees of freedom.

Additional constraints can be applied to objective function arguments and admissible displacements:

$$\sigma_i \in \langle \sigma_{\min}, \sigma_{\max} \rangle, \max [q_i(t) \in A] \leq q_i^{\max} \quad (4)$$

where: σ_i - yield stress in active element i of adaptive structure A , $\sigma_{\min}, \sigma_{\max}$ - minimal and maximal yield stress in active elements, q_i - displacement of degree of freedom i , q_i^{\max} - maximal admissible displacement.

4.3 Numerical example

The numerical example presents an adaptive truss with base structural module of 4m x 4m equipped with energy dissipation zones embedded into the main structure. Position of active zones and model of dynamic load follows from an assumption that the structure can be located offshore and subjected e.g. to an impact of docking service ships or cracking ice.

Dynamic load is modelled as an impact of two rigid masses (750kg) with initial velocity $v_0=8\text{m/s}$ attached to selected nodes of the adaptive zone and the objective function is to minimise horizontal acceleration for selected control node (c.f. Fig. 4.2). Additionally, the truss is subjected to self-weight load and vertical load $F_1=F_2=10\text{kN}$ simulating auxiliary equipment located at the top level.

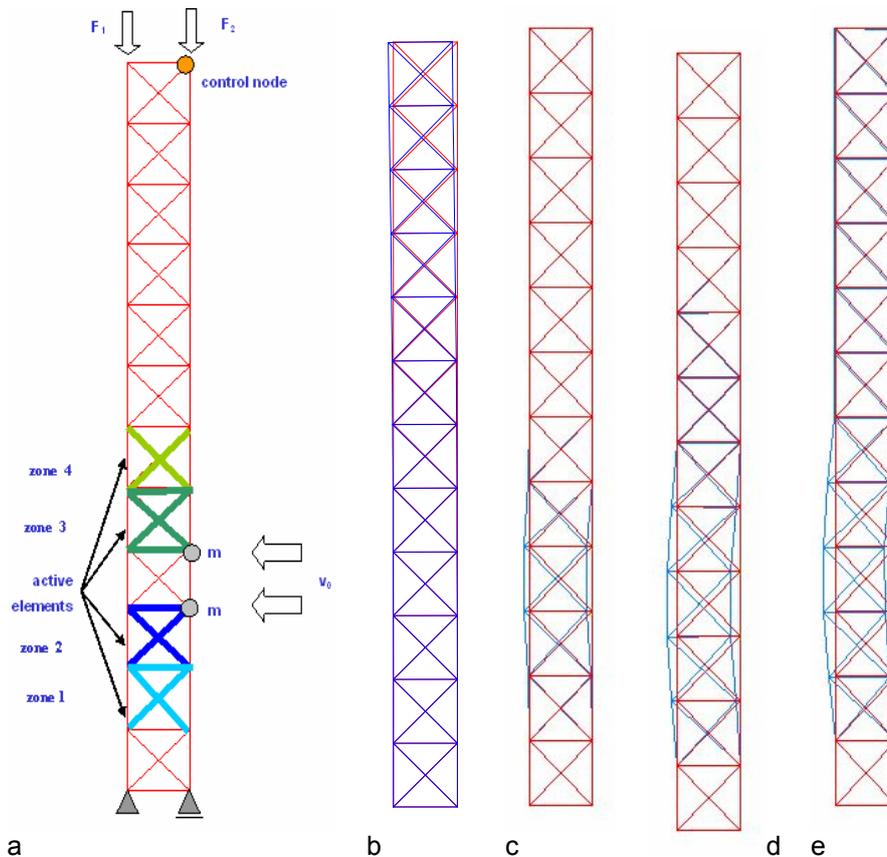


Figure 4.2: a) Model of an adaptive structure, b) passive deformation, c-e) sequence of optimal deformation

The adaptive zone consists of four structural modules located in the lower part of the structure. Yield stress levels of structural fuses take values from the range of $\langle 0.1\text{MPa}, 600\text{MPa} \rangle$. All other structural members have the highest admissible yield stress of 600MPa . In order to provide stability of the deformed configuration, maximal allowable displacement was constrained to $q_{\max} < 0.8\text{m}$.

Proper positioning of adaptive zones and application of optimal yield stresses in structural fuses allowed for full dissipation of kinetic energy of the impact in time of 400ms (Fig. 4.3 c) and localization of permanent plastic deformations only in adaptive zones.

Impact indices I_2 and I_3 calculated in case of passive response and optimal solution are presented in the tab.1 along with values of yield stresses in four adaptive zones of the structure.

Index	Passive structure	Optimal adaptation
	$\sigma_1 = 600\text{MPa}$ $\sigma_2 = 600\text{MPa}$ $\sigma_3 = 600\text{MPa}$ $\sigma_4 = 600\text{MPa}$	$\sigma_1 = 5.0\text{MPa}$ $\sigma_2 = 6.0\text{MPa}$ $\sigma_3 = 3.0\text{MPa}$ $\sigma_4 = 0.6\text{MPa}$
$I_1 \text{ [m/s}^2 \text{]}$	2642	115
$I_2 \text{ [m/s}^2 \text{]}$	7980	581

Table 1: Results for passive response and optimal adaptation

For the analysed structure it is possible to provide reduction of peak acceleration by the factor of 20 and over tenfold reduction of average acceleration level at the controlled node.

Time evolution of acceleration of the controlled node for the passive and optimal solution are presented in Fig. 4.3 a-b, which shows that structural adaptation to impact load not only provides very high reduction of dangerous acceleration levels but also influences frequency spectrum of the dynamic response.

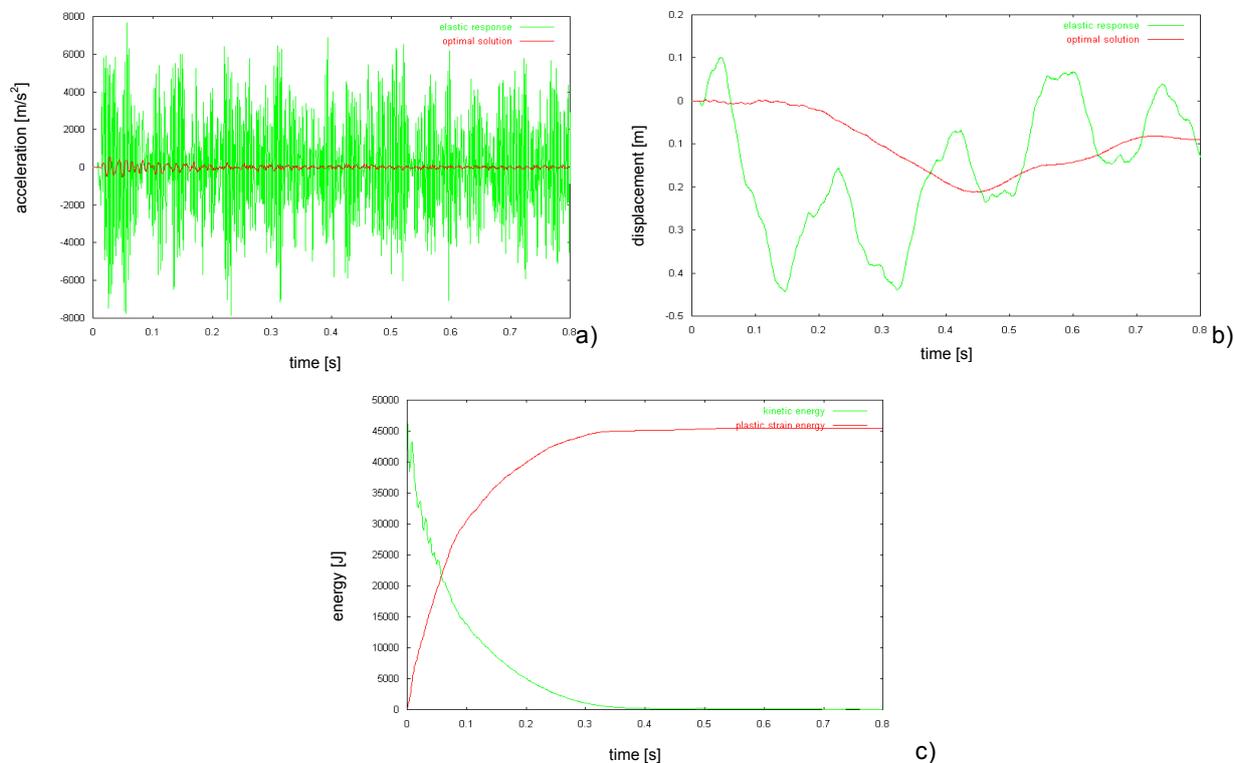


Figure 4.3: a)-b) Evolution of acceleration and displacement for optimal and passive solution; c) Evolution of kinetic and plastic strain energy for optimal solution

Numerical analyses of selected structure presented in the paper proved, that the process of adaptation has positive influence on structural response. Carried out optimisation significantly minimised horizontal accelerations of selected control nodes. This effect is especially important in case of truss structures supporting sensitive mechanical or electronic equipment located at the top level e.g. wind turbines, radar or systems for teletransmission.

5 ADAPTIVE INFLATABLE STRUCTURES

5.1 The concept

Adaptive Inflatable Structures are a special technology for Adaptive Impact Absorption which is based on effective use of compressed gas and control of its pressure during the impact process⁷. AIS are rigid or deformable structures containing sealed chambers filled with compressed gas and additionally equipped with fast inflators and controllable high performance valves²¹ which enable real-time adjustment of actual values of pressure.

The design of adaptive inflatable structure involves proper choice of its geometry and division into pressure chambers, as well as determination of required properties of inflators and controllable valves. The process of adaptation is executed in two main stages. After impact detection and identification each chamber is inflated to appropriate initial pressure which provides optimal initial compliance of the structure. During impact the valves mounted in internal partitions and external walls control the gas flow between the chambers and outside the structure. In this manner, change of pressure in different parts of the structure may be controlled and actual stiffness and global dynamic characteristics of the inflatable structure can be adjusted in real-time during subsequent stages of impact. This, in turn, allows for optimal dissipation of the impact energy and mitigation of dynamic response of both protected structure and impacting object.

The form and shape of Adaptive Inflatable Structure depends on its particular application. The inflated structure may act uni-directionally (as cylinder enclosed by piston), it may be a thin-walled steel structure or completely deformable cushion made of rubber or fabric. Moreover, AIS may constitute an independent system, it may be attached to impacting object or, alternatively, to protected structure. The concept of Adaptive Inflatable Structure comprises external airbags for emergency landing (Fig. 5.1a)²², torus shaped fenders protecting offshore towers (Fig. 5.1b,c)²³, as well as, described in further part of this section, inflatable thin-walled crashworthy structures (Figs. 5.2-5.8)²⁴.

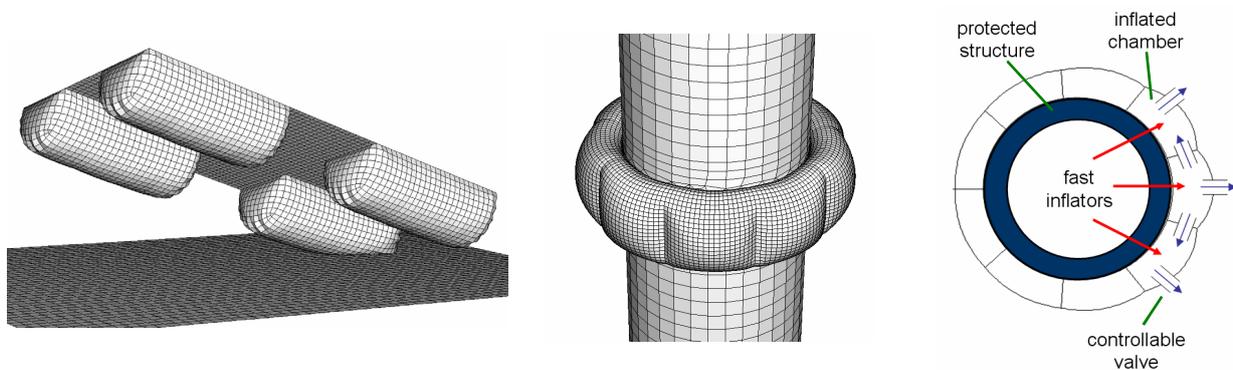


Figure 5.1: Adaptive Inflatable Structures: a) external emergency airbags; b,c) inflatable fenders for offshore structures

5.2 Crashworthiness of inflated thin-walled structures

Thin-walled structures are commonly used in transport and mechanical industry because of their large stiffness, durability and small weight. Moreover, thin-walled structures made of steel effectively absorb the energy of axial loading due to the process of plastic folding. The above features cause that longitudinal thin-walled steel elements are often applied in crashing zones of trains, cars and other energy absorbing structures.

In contrast, the concept presented in this section is focused on thin-walled structures subjected to lateral impact. In case of lateral loading, thin-walled structure easily undergoes buckling and local plastic yielding and, as a result, only small part of the impact energy is dissipated. However, as it will be shown in the following examples, filling thin-walled structure

with compressed gas and controlling its pressure during the impact process may significantly improve its characteristics and increase overall durability. Basic properties of inflatable thin-walled structures will be analyzed by using the experiment with inflated beverage can and numerical simulations of various steel structures subjected to lateral impact loading.

Basic experiment: buckling of the inflated can

In conducted experiment the can clamped at one end was subjected to the action of vertical force acting upwards and causing bending of the structure (Fig. 5.2). In the initial experiment an empty can was not sealed so internal pressure was equal to ambient pressure. During the experiment a value of vertical force was gradually increased. Sudden collapse of the structure was caused by buckling of the cylinder sidewalls, which occurred at a large area located between middle of the can and the support (Fig. 5.2a).

In the second stage of the experiment the cylinder was sealed and inflated with compressed gas under various pressures. Applied internal pressure causes additional distributed loading which prevents buckling by counteracting inward deformation of the can and by reducing compressive stresses in its upper wall. Along with increase of initial internal pressure the value of critical force was gradually raising (up to 3.9 times for pressure 0.6MPa) and the area of buckling was decreasing and moving in the direction of support, Fig. 5.2b. Finally, when initial internal pressure was too high a total destruction of the can occurred briefly after buckling because of the sudden burst in the vicinity of the support (Fig. 5.2c).



Figure 5.2: Deformation of the beverage can with internal pressure:
a) 0,1 MPa, b) 0,6 MPa, c) 0,8MPa

The experiment clearly reveals two important features of the inflatable thin-walled structures. Primarily, their durability to lateral loading and the amount of dissipated energy can be substantially increased by the use of compressed gas. On the other hand, application of high internal pressure is related to a danger of sudden destruction or blast of the structure, which implicates the requirement of precise real-time pressure control.

Numerical analysis of basic inflatable structures

In the following step several numerical simulations verifying potential beneficial influence of internal pressure were conducted. Three types of engineering structures where the usage of compressed gas might be advantageous were selected and an attempt of improvement of their crashworthy characteristics was performed. The following models were examined:

1. simplified model of the inflatable compartments inside double-layer hull of the ship, where appropriately adjusted internal pressure prevents total penetration by the impacting object (Fig. 5.3a);
2. model of inflatable door of the passenger car subjected to lateral impact where pressure of the gas causes substantial decrease of total deformation and better protection of the passenger's zone (Fig. 5.3b);
3. model of the inflatable road barrier where application of the pneumatic gas chambers allows to minimize adverse local effects (large deformation and local plastic yielding, Fig. 5.3c).

The above examples were utilized to investigate basic properties of inflatable thin-walled steel structures and to develop two-dimensional simplified model of inflatable barrier, which will be further used to elaborate precise pressure control algorithms.

* The experiment was performed by Mr. Rafał Chmielewski at IPPT PAN.

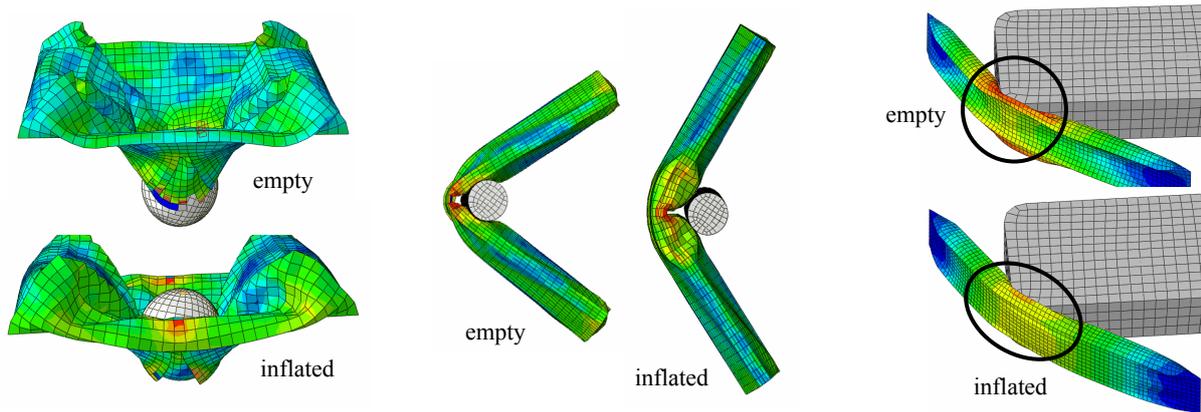


Figure 5.3: Influence of pressure on response of standard and inflated structures subjected to impact loading: a) hull compartment, b) door of a passenger car, c) protective road barrier

5.3 Adaptive inflatable multi-chamber barrier

Optimal strategies of pressure adjustment were developed for two-dimensional frame structure being simplified model of inflatable multi-chamber barrier (Fig. 5.4). The structure is subjected to impact loading defined by mass and initial velocity of the external rigid object. Deformation of the inflatable structure depends not only on parameters of the colliding object, but also on changes of pressures inside chambers during the impact process. In case of passive inflatable structure with closed chambers the changes of pressures are unambiguously defined in terms of their initial values. On the contrary, in case of adaptive inflatable structure the valves can be used to alter actual values of pressures and to control actual dynamic response of the structure.

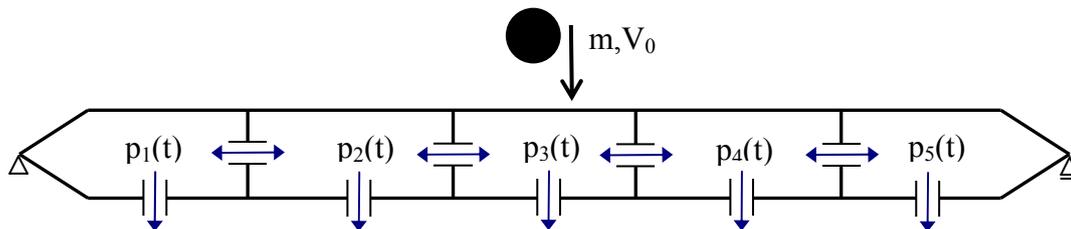


Figure 5.4: Two-dimensional frame structure considered in the optimization problem

Considered objectives of pressure adjustment were related to maximisation of the load capacity of the barrier and its adaptation to particular impact loading by control of impacting object deceleration, minimisation of inflation required to sustain given impact loading and obtaining desired final shape of deformation. In all cases the optimization was performed with respect to functions describing changes of pressures in particular chambers.

Maximization of the load capacity

In order to define the load capacity of the structure purely kinematical approach was applied, i.e. definition of the load capacity was based exclusively on structure deformation. The deformation was considered as admissible when two conditions were satisfied:

1. contact of the lower and upper beam of the frame did not occur,
2. maximal displacement of the lower beam did not exceed a limit value.

Finally, the load capacity of the frame was defined as maximal mass of the object striking the with predefined velocity, for which deformation of the frame remains admissible. Obviously, the load capacity depends on pressure of gas inside chambers of the frame. When the structure is not inflated its load capacity achieves its limit for a small mass of the impacting object due to collision of upper and lower beam. Increase of internal pressure causes that the deflection of the lower beam extends and load capacity of the structure rises.

The problem solved was to maximise the load capacity of the structure with respect to continuous functions describing changes of pressure inside the chambers. Mathematical

formulation utilizes definitions of two limiting deformations: Γ_{Sq}^1 where final distance between beams tends to zero and Γ_{Sq}^2 where maximal displacement of the lower beam is achieved. Moreover, two introduced functions $\Gamma_{Sm}^1(\mathbf{p})$ and $\Gamma_{Sm}^2(\mathbf{p})$ allow to determine corresponding critical masses of the impacting object for each predefined change of pressures defined by vector \mathbf{p} , Fig. 5.5. The proposed methodology of solution effectively utilizes the fact that both kinematical conditions are counteractive and load capacity achieves maximal value when both limiting deformations are obtained.

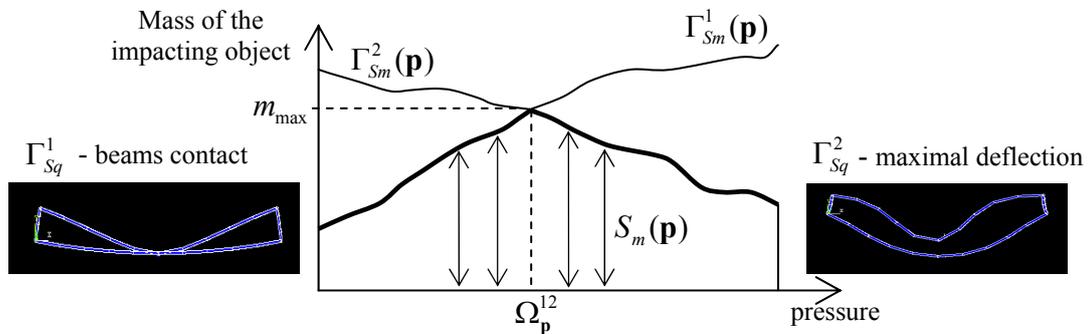


Figure 5.5. Geometrical interpretation of the considered optimisation problem for a simple structure with single pressure chamber

Conducted numerical simulations concerned single- and multi-chamber barriers with various boundary conditions and various models of the impact loading. Pressure inside chambers was either assumed to remain constant or to decrease linearly during the impact process.

Presented example refers to maximisation of the load capacity of three-chamber inflatable barrier loaded in the middle of the upper beam (Fig. 5.6). In such case the control function \mathbf{p} has only two arguments indicating pressures in lateral and middle chambers. Initially, constant value of pressure during the whole impact process was considered. The highest increase of load capacity (6.1 times) was obtained for maximal allowable pressure in lateral chambers and significantly smaller pressure in the middle one. In the second example linear decrease of pressure was assumed. In optimal solution middle chamber is almost tenfold more inflated than the lateral chambers and pressure is totally reduced exactly at time instant when the impacting object is stopped. As a result structure load capacity is increased 9.02 times in comparison to generic case of an empty barrier.

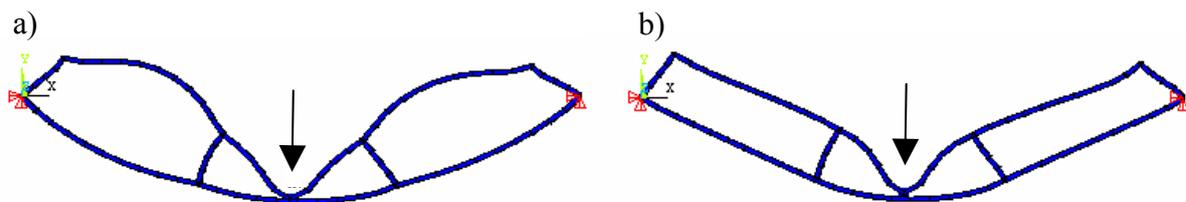


Figure 5.6 Deformation of the optimally inflated frame impacted by maximal mass: a) constant pressure; b) gradual linear decrease of pressure

Methods of adaptation to impact loading

Other numerical examples concern adaptation of the inflatable barrier to a given impact loading. In this type of problems impact scenario will be arbitrarily defined (by impact mass, velocity and location) and pressure adjustment will be focused on control of impacting object deceleration and obtaining desired final deformation of the structure.

Control of impacting object deceleration may be aimed at reducing its maximal value or, alternatively, at maintaining its high level in order to confine maximal displacement of the impacting object. Herein, only the former case will be briefly discussed. Time-history of colliding object deceleration depends whether the collision of both beams of the frame occurs. In case when impact energy is high and causes beams collision, a steep peak of deceleration arises and it is followed by gradual increase of deceleration level being the effect of joint resistance of both beams (Fig. 5.7, uncontrolled case).

Two basic methods of deceleration minimisation were proposed: 'local approach' based on decomposition of the problem into a series of local ones related to subsequent time instants and 'global approach' based on direct searching of parameters of functions describing change of internal pressure in terms of time. The numerical example presents application of the second method for reduction of impacting object deceleration in single chamber frame. Precise adjustment of two introduced parameters (inflation time t_{inf} and inflation pressure p_{inf} , Fig. 5.7a) provides a relevant compromise between increase of stiffness of the upper beam caused by internal pressure and an increase of global stiffness due to collision of the beams. As a result, the level of impacting object deceleration remains smooth during the whole process and it decreases from $55,02\text{m/s}^2$ (or $41,5\text{m/s}^2$ excluding peak) to $34,9\text{m/s}^2$, Fig. 5.7b.

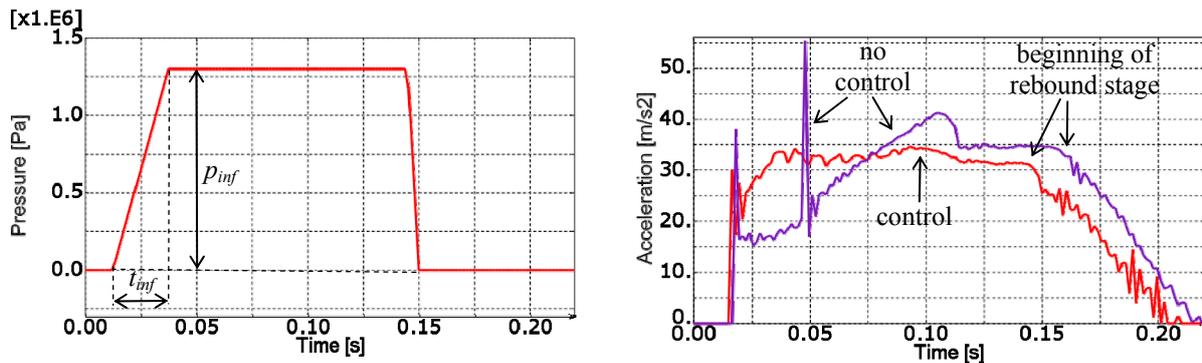


Figure 5.7 Adaptation aimed at minimisation of impacting object deceleration: a) optimal change of pressure in time, b) comparison of deceleration for passive and controlled structure

The second goal of adaptation is to control the process of structure deformation in order to achieve predefined final configuration, regardless of applied loading. In case of considered inflatable thin-walled frame, the assumed objective is to obtain maximal compression of the selected chambers, i.e. to minimize distance between upper and lower beam of selected chambers in final deformation. Such formulation allows to control locations of arising of main plastic hinges which are the major mechanism of energy dissipation. Moreover, maximal compression of the chamber entails substantial amount of impact energy used for gas compression and the possibility of dissipating this energy in a controlled way.

Numerical example presents control of deformation of five-chamber inflatable thin-walled frame. Typical response to the impact loading applied over peripheral left chamber involves large deformation of the impacted chamber and insignificant deformation of the other ones, Fig. 5.8a. Under certain inflation of the left part of the frame the structure becomes sensitive to the value of pressure and deformation shape changes. Precise adjustment of initial value and intensity of pressure release allows to obtain deformation of the second or alternatively third (central) chamber of the frame, Fig. 5.8b,c. The qualitative modification of the structure deformation is associated with a change of maximal deflection of the frame and with a change of total time of deformation.

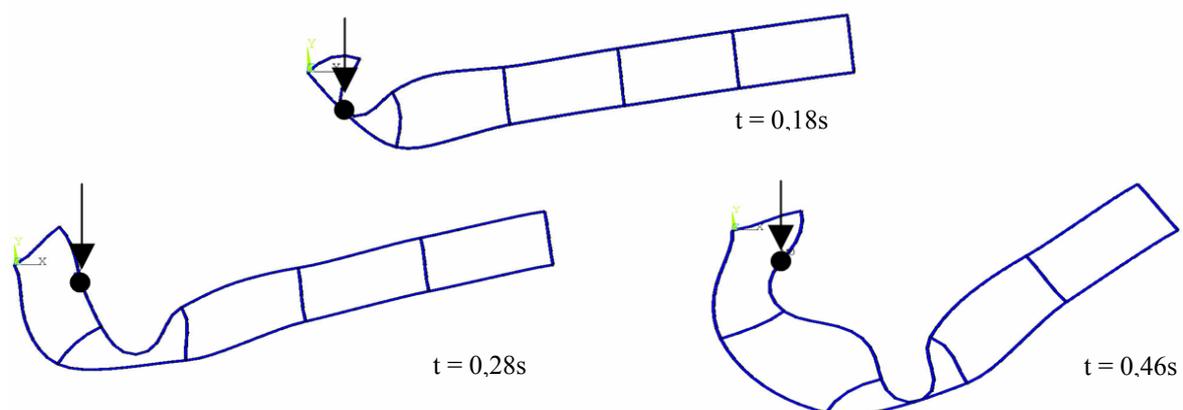


Figure 5.8: Various deformations of the frame obtained in case of lateral impact: a) no inflation, b) and c) inflation causing change of deformation

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