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ADAPTIVE PRESSURIZED STRUCTURES FOR IMPROVED IMPACT ABSORPTION.

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Abstract. *The paper presents briefly the concept of controlling dynamic response of the thin-walled structures by filling them with compressed air and its controlled release during the impact process. The succesful result of using this method is strongly dependent on a proper pressure adjustment inside the structure according to the impact type and direction. The paper is focused on developing strategy for optimal distribution and release of pressure and corresponding software tools which contain procedures for numerical simulation of the impact process and optimization algorithms. Considered objective functions are formulated basing on conditions concerning: possibly soft absorption of the impact, dissipating the highest amount of energy, using the lowest pressure values, achieving assumed deformation of the structure. The results prove that pressure adjustment strategy has a significant influence on the deformation process and on energy absorption. Conducted simulations indicate that pressurised structure can easily change its dynamic properties and is possible to adapt to variable load cases and impact types.*

1 INTRODUCTION

Thin-walled structures are commonly used in car and mechanical industry because of their huge durability, stiffness and small weight. They efficiently absorb energy of the front impact due to the process of folding. Estimation of critical dynamic forces and dissipation capabilities for several types of thin-walled structures obtained by simplified analytical models can be found in classical crashworthiness literature cf. Johnes(1). The problem of increasing the load capacity of such structures under axial loading by using pressure, structural fuses and pyrotechnik detachable connectors was successfully examined by Gren(2), Knap(3), Ostrowski, Griskevicius and Holnicki-Szulc(4).

In this paper we focus our attention on lateral impact where substantial difficulties might appear. The thin-walled structure undergoes large deformations and local plastic yielding but only small part of the impact energy can be dissipated. Significant improvement of the structure properties by filling it with compressed air and its controlled release was proposed by authors in their previous paper on this topic, cf. Graczykowski, Chmielewski, Holnicki-Szulc(5). Filling with gas in the initial stage of the lateral impact results in increasing the load capacity of the structure and prevents its huge deformations. The purpose of the controlled release of pressure is to dissipate energy accumulated in gas and to confine accelerations to admissible level. Initial value and change of pressure in time must be adjusted according to the type and direction of impact. Additional advantages can be achieved by dividing structure into pressurized packages and controlling values of pressure in every cell separately. Compressed air has also a beneficial influence on the buckling behavior of the structure, since it increases the value of critical force. These features of the pressurized structures were confirmed by experiment conducted on aluminium can. Structures adapted to impact by using compressed gas will be further called Adaptive Pressurized Structures (APS).

2 CORRESPONDING OPTIMIZATION PROBLEMS

This paper is aimed at developing a strategy for optimal distribution and release of gas in pressurized packages. For this purpose the above considerations are formulated as optimization problem. The structure being optimized is a simple two dimensional frame (cf. Fig.1) which could serve as a basis for a car door design. The structure may be divided into various number of packages and it may have clamped or sliding supports. The frame is loaded on the upper beam which is modeling lateral (non-axial) impact. Material and geometrical nonlinearities are taken into account. The material is elasto-plastic with the hardening, large deformations of the frame are considered.

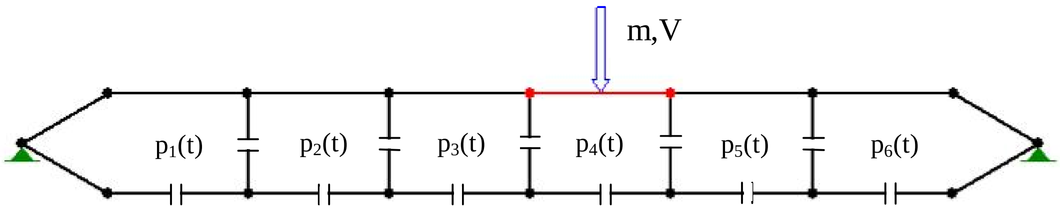

Figure 1: Structure divided into pressurized packages considered in the optimization problem.

The optimization is performed with respect to changes of pressure in every package. The objective function is based on the following criteria: dissipation of the highest impact energy, possibly soft absorption of impact, applying the smallest pressure values for given impact, achieving assumed deformation of the structure. The subsequent optimization problems, together with methods of solution and results are presented in the further part of the paper. Derived objective functions and constraints could have a fairly complicated implicit form since they are obtained from nonlinear dynamic analysis. Constraints are formulated basing on kinematic conditions imposed on maximal displacement and on the shape of frame destruction.

Solving mentioned problems requires using Finite Element software and optimization procedures. In this case a linkage between Ansys and Matlab packages is effectively used. The major application is Matlab, in which model parameters are stored and a batch file for FEM analysis is created. Ansys is launched within Matlab to conduct nonlinear transient dynamic analysis by means of Newmark algorithm and Newton-Raphson procedure, cf.[6] and to calculate value of the objective function. Afterwards this function is minimized by Matlab built-in optimization procedures.

3 DISSIPATION OF THE HIGHEST ENERGY

This chapter concerns examination of overall properties of the pressurized structure. On this stage we do not assume a detailed impact scenario, but we investigate how much we can improve the structure by pressurizing. Hence the objective function of the optimization problem will be based on condition of dissipating the highest impact energy.

The dynamic system is described by well-known equation of motion in its nonlinear form with initial conditions imposed on unknown function and its first derivative:

$$\mathbf{M}\ddot{\mathbf{q}}(t) + \mathbf{C}\dot{\mathbf{q}}(t) + \mathbf{K}(\mathbf{q})\mathbf{q}(t) = \mathbf{F}(\mathbf{q},t) \tag{1}$$

$$\mathbf{q}(0) = \mathbf{q_0} \text{ , } \dot{\mathbf{q}}(0) = \dot{\mathbf{q}}_\mathbf{0}$$

The impact subjected to the structure upper beam is modeled by concentrated mass of the hitting object which is included in mass matrix and its velocity being one of the initial conditions. We assume that the impact velocity is established so the load capacity will be measured only by the hitting object mass. Values of pressures inside the packages influence right hand side load vector $\mathbf{F}$ and displacements $\mathbf{q}$ likewise. Thus, dynamic properties of the structure can be controlled by means of internal pressure. The solution of the problem (1) can be written by implicit nonlinear vector function $\mathbf{q}(m,\mathbf{p},t)$ where m is the mass of the hitting object, vector $\mathbf{p} = \{p_1(t), p_2(t),..., p_n(t)\}$ contains functions describing change of pressure in every cell. Function $q_m(m,\mathbf{p},t)$ denotes displacements of the node to which impact is subjected and t_{stop} indicates time of braking the mass i.e. at time when velocity of the hitting object approaches zero for the first time.

We will apply kinematic approach, which means that the conditions defining destruction of the structure will be based on its deformation shape. The admissible deformation of the structure is denoted S_q and is constituted if there is no collision between the mass and the lower span $D(m,\mathbf{p},t) > 0$ and when maximal displacements of the lower span do not exceed limit value $q_{\max} \le q_{adm}$.

Engineering formulation of the optimization problem is as follows: find maximal mass which can be subjected to the structure appropriately filled with pressure and do not violate kinematic conditions imposed on structure deformation. Thus we are searching for maximal mass and corresponding distribution of pressure as well. Straightforward mathematical formulation can be written:

$$\text{Find: } \max_{m,\mathbf{p}} \{ m | \; \mathbf{q}(m,\mathbf{p},t) \in S_q \} \tag{2}$$

where S_q indicates allowable deformation

The detailed reformulation and simplification of this problem will not be presented here since it can by found in the paper by Graczykowski, Holnicki-Szulc, cf [7]. We will confine considerations to conclusion that in optimal solution both conditions on deformation are on their limit. This approach can be applied for finding optimal distribution of pressures in three-cell pressurized structure fixed with no sliding (cf. Fig. 2). The loading is performed by object hitting the frame in the middle of the upper span with initial velocity equal to 2m/s. We assume that pressures inside packages do not exceed 1600 kN/m and that they are constant during the whole analysis. Hemce, vector **p** has two constant components p_1 and p_2 which indicate pressures in lateral and middle cell, respectivelly. Impact subjected to this structure causes large deformations resulting in change of packages capacity which must be taken into account. To keep the pressure on constant level we have to release the air volume equal to change of chamber capacity e.g. by opening exit valves. Finally the load capacity is increased 6,1 times and is achieved for the maximal pressure p_1, cf. Table 1.

$\mathbf{p}_1(0)$ [kN/m]	$\mathbf{p}_2(0)$ [kN/m]	$\mathbf{p}_1(t_{stop})$ [kN/m]	$\mathbf{p}_2(t_{stop})$ [kN/m]	$q_{\max}$ [m]	t_{stop} [s]	**m** [kg]
0	0	0	0	0,04	0,152	**7596**
1600	1147	1600	1147	0,18	0,213	**46374**
400	3925	0	0	0,18	0,265	**68489**

Table 1. Comparison of structure load capacity for different values of pressure (central impact)

The second case considered concerns linear decrease of pressure in all packages. The time when pressure approaches zero is assumed to be equal to the time of braking the mass. This time is calculated beforehand and changes within the range 0,15 - 0,3s according to the initial values of p_1 and p_2, which are limited to 4800 kN/m. The highest mass is 9,01 times larger than the initial one and it is found for low value of pressure p_1. Detailed results for both cases are presented in Table 1 and corresponding deformation of the structure is presented in Fig. 2.

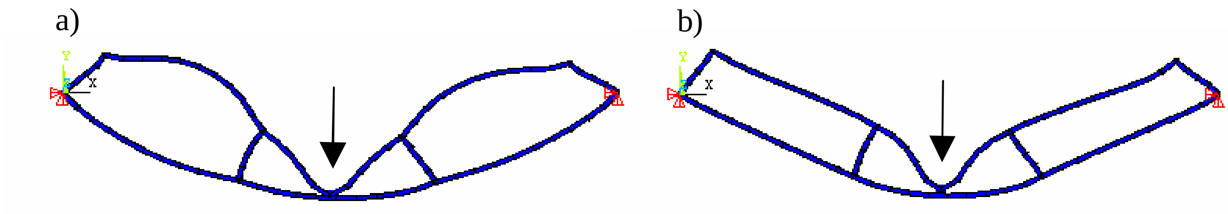

Figure 2: Deformation of the optimally pressurized structure loaded by maximal mass:
a) constant pressure; b) linear release of pressure

Load capacity can be also examined in the case of impact situated over the left chamber. Kinematic criteria for admissibility of structure deformation remain valid. Initial load capacity of the structure is over 40% smaller than in the case of central impact and it is exhausted when collision between upper and lower beam occurs. Pressurizing central package without release is not beneficial, since it causes excessively large outside displacements in central package and decrease of distance between spans in lateral chambers. Pressurizing only right package has almost no influence on dynamic properties of the frame. Due to these facts only filling left package with compressed air will be examined precisely. Displacement of the lower span is the largest below left package but it remains relatively small (0,121m) even for highest arbitrary assumed pressure value of 2500 kN/m and corresponding mass 52000 kg.

$\mathbf{p}_1(0)$ [kN/m]	$\mathbf{p}_1(t_{stop})$ [kN/m]	$q_{\max}$ [m]	t_{stop} [s]	**m** [kg]
0	0	0,087	0,112	**4350**
2500(max)	2500(max)	0,121	0,192	**52000**
5000(max)	0	0,143	0,248	**76000**

Table 2. Comparison of structure load capacity for different values of pressure (lateral impact)

Similar situation occurs when linear decrease of pressure is assumed and time of pressure being zero is achieved at t_{stop}. The most beneficial is pressurizing only left package. After applying maximal arbitrary assumed pressure equal initially 5000kN/m mass of 76000 kg can be subjected to the structure. Load capacity is still exhausted due to collision of spans. Lower beam displacement is equal 0,143 m so it does not exceed limit value. When both left and central chamber are pressurized, load capacity is increased over 18 times in comparison to the initial one and is equal about 79000kg. The necessity of pressurizing two packages and, by doing so, introducing more energy to the system is a great disadvantage of this second solution.

4 SOFT ABSORPTION OF THE IMPACT

The second purpose of applying pressure into the structure is to alleviate the impact by changing structure stiffness during collision. In this section we will assume given scheme of impact so mass of the hitting object will not be design variable in further analysis. Our goal is to control displacement, velocity and acceleration of the hitting object. The most expedient trajectory is a second order curve. By using this curve we can obtain linear descent of the velocity and constant value of acceleration during the whole process. Displacement of the node with applied mass is assumed to change according to:

$$q_m^{opt}(t) = V_0 t + \tfrac{1}{2} a t^2 \tag{3}$$

where: initial velocity of the object $V_0 = 2m/s$, level of acceleration $a = -20m/s^2$ and time of the whole process $t = 0{,}1s$. Assumed trajectory (3) must be always situated above initial displacement curve since applying pressure we cannot increase structure compliance. The advantage of this procedure is reduction of penetration by hitting object.

Mathematical formulation of the optimization problem can be written as follows:

$$\text{Find: } \min\left\{\Phi(\mathbf{p}(t)) \;\middle|\; \mathbf{q}(m,\mathbf{p},t) \in S_q\right\} \tag{4}$$

$$\text{where } \Phi(\mathbf{p}(t)) = \int_0^{t_{stop}} \left[q_m(t) - q_m^{opt}(t)\right]^2 dt$$

and $q_m(t)$ is the component of nonlinear implicit function $\mathbf{q}(m,\mathbf{p},t)$. The objective function is defined here as an integral obtained from a difference between actual and assumed displacement calculated over a given time domain. Such formulated problem seems quite difficult to solve since we have to search through infinite number of functions $\mathbf{p}(t)$ and assuming this function as a polynomial does not give satisfactory results. However, while using time integration within Finite Element Method we can discretize the objective function in a given time domain as we do it with function of displacements. This way we obtain decomposition of the initial optimization problem into series of simpler ones, where objective function and design variables are defined in every moment in time:

$$\Phi(\mathbf{p}(t_k)) = \left[q_m(t_k) - q_m^{opt}(t_k)\right]^2 \tag{5}$$

The introduced optimization problem can be solved for several numbers of packages in the structure, however pressurizing only one of them is usually sufficient to fit both displacement curves. The most efficient is pressurizing the chamber to which impact is subjected. Structure here considered consists of only one package and has sliding support. A mass hitting the structure is equal to 500kg. Pressure in every single time step is adjusted to fit the displacement of the mass to the assumed curve. Results obtained from the previous steps are effectively used on the following ones. Ansys built-in procedures are applied to conduct optimization process. The resulting change of pressure is shown in Fig 3a. High value of pressure is necessary at the beginning of the impact and then the curve of pressure is declining gradually.

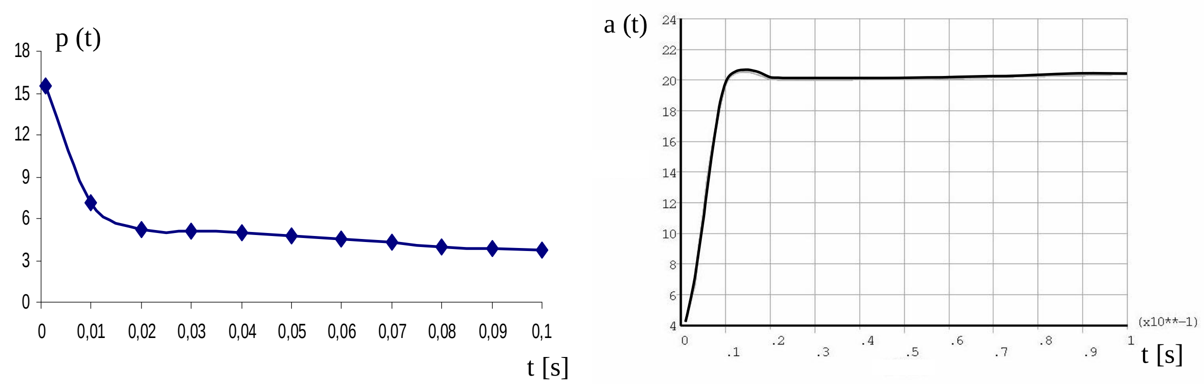

Figure 3: Results of the optimization: a) change of pressure in time; b) resulting acceleration of the hitted joint

In this example the objective function was diminished almost to zero so the assumed and obtained curves overlap and the level of the acceleration is almost constant, see Fig. 3b. It was possible since for adjusted values of pressure kinematic conditions imposed on a frame were not violated. Sometimes the necessity of keeping deformation of the structure in allowable range causes that objective function can not be obtained with such precision.

5 USING THE LOWEST VALUES OF PRESSURE

The subsequent problem considered is adapting the structure to assumed impact (of energy not exceeding those found in Sec. 3) by using smallest possible inflation of the structure or the smallest amount of introduced energy. The pressures will be adjusted under assumption that they are constant during the whole process, but then their release will be realized as planned in Sec. 4. For the small value of mass structure may sustain impact without inflation. When the mass is larger set of admissible pressures may not contain point $\mathbf{p}=0$ and pressurization of the structure is necessary. Finally critical mass exists for which only one combination of pressures is possible (cf. Sec. 3). For mass higher than $m_{\max}$ there is no solution of the problem considered.

This time the objective function is expressed explicitly by design variables and it is defined as a sum of pressures or a sum of their squares. Optimization problem can be defined in the following way:

$$\text{Find: } \min\left\{\Phi(\mathbf{p}))\ \middle|\mathbf{q}\in S_{\mathbf{q}}\right\} \tag{6}$$

$$\Phi(\mathbf{p}(t))=\sum p_i V_i \text{ or } \Phi(\mathbf{p}(t))=\sum (p_i)^2 V_i$$

where i=1...k and k is the number of cells in APS. The constraints imposed on admissible deformation remain nonlinear. According to considerations in [7] minimum of the objective function is expected to be found in the situation of collision of the spans at the moment of braking the mass. We assume that the function of mass causing contact of the beams $m^1(\mathbf{p})$ can be approximated by 'linear' equation in the form:

$$m^1(\mathbf{p})=a_0+\sum_{i=1}^{k} a_i p_i \tag{7}$$

where a_0 is the mass which can be applied to the structure with no pressurization, a_i indicates influence of the pressure p_i on the value of the maximal mass $m^1(\mathbf{p})$. To obtain better precision it can be also approximated by function of higher order. We have to calculate intersection of this surface with the surface of constant mass m^*:

$$a_0+a_1 p_1+a_2 p_2=m^* \tag{8}$$

From this equation we can find line $p_2(p_1)$ on which optimal solution is located. If the mass m^* is close to $m_{\max}$ found in Sec. 3 we have to search through the line $p_2(p_1)$ starting from point $p_1=0$ and for each combination of pressures we have to check whether the condition on maximal displacement is not violated.

Further we will analyze three cell APS loaded in the middle of the upper span previously examined in Sec. 3. Coefficients a are found by the least squares method and the value of the mass is assumed to be $m^*=40000\,kg$, which is significantly lower than m^*. This fact lets us neglect limit displacement condition and search for optimal pressure over all initially assumed range of pressure. We obtain a problem of linear programming with objective function given by:

$$\Phi(\mathbf{p})=2p_1V_1+p_2V_2=(2V_1-\tfrac{a_1}{a_2}V_2)p_1+\tfrac{m^*-a_0}{a_2}V_2 \tag{9}$$

In this situation $a_1 \ll a_2$ so the objective function is increasing in terms of p_1 and its minimum is achieved for $p_1=0$. Value of p_2 obtained from (8) is equal to $1199{,}7\,\frac{kN}{m}$. From formulation (9) we conclude that packages dimensions have meaningful influence on the results. It is planed to introduce packages dimensions as a design variable in future considerations. The same problem was also solved for objective function defined in quadratic form, cf (6). Function $\Phi(\mathbf{p})$ achieves its minimum for $p_1 = 103{,}1\frac{kN}{m}$. Value of p_2 obtained from (8) is equal to $1181{,}7\frac{kN}{m}$. Hence, the formulation of the objective function as a sum of pressure squares results in distributing small amount of pressure to lateral cells in optimal design.

6 ASSUMED DEFORMATION OF THE STRUCTURE

In the last example, the considered objective function is based on final deformation. Our goal is to get all packages crushed i.e. obtain minimal distance between upper and lower beam in every cell. In such situation the largest quantity of the gas has to flow out from the structure and the largest amount of energy is dissipated. We control kinematics of the structure as in Sec. 4, however, the objective function (assumed deformation) is not defined in every moment in time. The second difference is that the deformation of the whole structure is assumed, not only displacements of one node.

Mathematical formulation of the problem is given :

$$\textit{Find} \ \min \left\{ \Phi(\mathbf{p}(t)) \middle| \mathbf{p}(t) \in \Omega_p \right\} \tag{10}$$

$$\textit{where}: \ \Phi(\mathbf{p}(t)) = \sum_{i=1}^{n} D_i(q_u(t_x), q_l(t_x))$$

and Ω_p denotes arbitrary assumed set of all vectors of pressures. The objective function is defined as a distance between two nodes belonging to opposite spans which are closest to each other. We try to diminish this distance to zero. Unfortunately, we do not know which nodes will collide and when will it happen (this time could be different for each package). We also cannot decompose the problem to the series of simpler ones. For the simplicity we assume linear decrease of pressure so we have only two design variables in every package. Deformation of the structure does not have to be contained in the set S_q defined by (3).

The above problem of optimal pressure distribution was examined for different position of loading in three-cell APS with one sliding support. The strategy of filling with pressure is strongly dependent on the scheme of impact so load identification is very important at the preliminary stage of the whole process. In this case our goal was to distribute the destruction

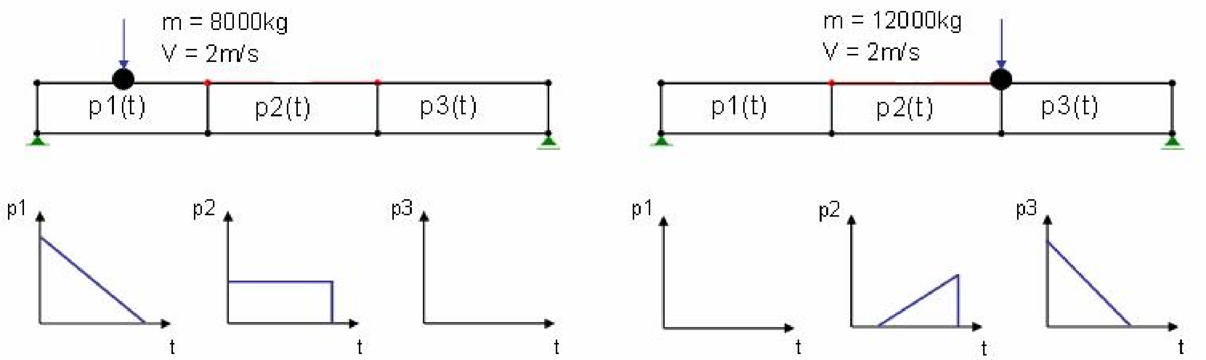

Figure 4: Strategy of the pressure distribution during lateral impact: a) over left chamber, b) over right partition

caused by lateral impact into two adjacent packages and get them both crushed. In considered cases external packages are most exposed to destruction so we pressurize it strongly at the initial stage of impact. Then we can release pressure, but we have to move it to the middle cell to avoid its total destruction, cf. Fig. 4.

Good results were also obtained in controlling destruction shape of five cell APS with stiff partitions, cf. Fig. 5. Having five packages we are able to adjust pressure precisely in different parts of the structure. Under certain inflation the structure becomes sensitive to the value of pressure, deformation shape changes and we can control places of arising plastic hinges. Applying this strategy we are able to distribute lateral concentrated loading into other chambers of the frame and change time of the deformation.

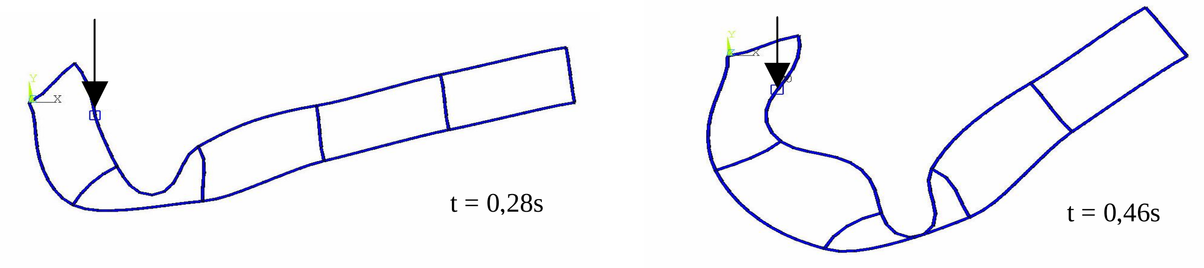

Figure 5: Distribution of the impact subjected on the left side of the frame to other chambers

By means of using high pressure in the central cell we can also distribute central concentrated loading into two sides of the frame, cf. Fig. 6. The benefit that we gain is that two plastic hinges are created instead of one so more energy can be dissipated. Limitation of pressure to positive values causes that crushing all packages is not feasible.

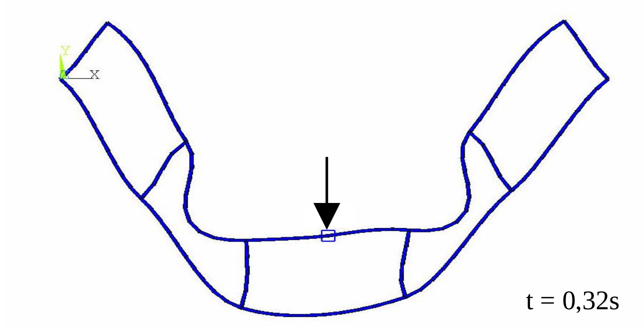

Figure 6: Crushing of the lateral chambers during central impact.

7 CONCLUSIONS

- APS is based on a concept of pressurized packages within thin-walled structure and controlled pressure outlets (cf. patent pending [8]).
- Pressurized structure can be easily adapted to different load conditions by means of appropriately chosen change of pressure in every package.
- Dynamic properties of APS can be formulated as nonlinear optimization problem
- Optimization algorithms were used to:
  a) increase energy absorption properties
  b) alleviate results of impact

c) introduce the smallest energy to the system
d) control kinematic response of the structure

APS equipped with sensors able to detect and identify (in real time) the impact load can serve as on-line adaptive impact absorbing system controlling injection and release of pressure in structural sections. The optimal control strategies have to be pre-computed and stored in memory of hardware controllers to make the process feasible. Motivations for the particular optimization problems discussed in the paper are the following:

a) Maximization of load capacity (chapter 3) is useful in the process of designing of the APS system serving for a given range of loads
b) and c) Smoothing impact absorption (chapter 4) or minimizing the gas pressure (chapter 5) can be used as the real time strategy of adaptation to the detected (and identified) impact load
c) The formulation presented in chapter 6 can be treated as an alternative for the problem discussed in chapter 3.

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