Article citation info:
FERDYNUS M. An energy absorber in the form of a thin-walled column with square cross-section and dimples. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2013; 15 (3): 253–258.

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AN ENERGY ABSORBER IN THE FORM OF A THIN-WALLED COLUMN WITH SQUARE CROSS-SECTION AND DIMPLES

ABSORBER ENERGII W POSTACI CIENKOŚCIENNEGO SŁUPA O PRZEKROJU KWADRATOWYM Z WGŁĘBIENIAMI*

The object of the research was a thin-walled energy absorber made of aluminium in the form of a column having square cross-section and a series of dimples in the corners. As the possibilities of practical applications of the absorber appear to be considerable, the paper presents prospects of building a palletization head. An influence of the global initial deflections on sub-critical form of the equilibrium path was examined. This was an attempt to assess the structure's susceptibility to deviations of the column's axis from the ideal one. In the article a way of the column's model construction was described in detail. The model takes into account the corner dimples, the initial deflections and the perturbations caused by geometrical imperfections. Advantages of the new solution were presented in comparison with a column having smooth walls.

***Keywords**: energy absorber, damage, palletization head.*

Obiektem badań jest cienkościenny absorber energii w postaci słupa o przekroju kwadratowym z szeregiem wgłębień w narożach wykonany z aluminium. Możliwości zastosowań praktycznych wydają się duże, przedstawiono perspektywę dotyczącą budowy głowicy do paletyzacji. Bada się wpływ globalnych ugięć wstępnych na podkrytyczną postać ścieżki równowagi, jako próbę oceny wrażliwości tej konstrukcji na odchylenia od osi idealnej słupa. W pracy przedstawiono szczegółowo sposób budowy modelu słupa z wgłębieniami oraz ugięciem wstępnym i zaburzeniami imperfekcjami geometrycznymi. Zalety nowego rozwiązania przedstawiono w porównaniu ze słupem o gładkich ścianach.

***Słowa kluczowe**: absorber energii, zniszczenie, głowica do paletyzacji.*

1. Introduction

During the operation of the machinery sometimes a collision and damage takes place in result of a human mistake or a machine's failure. In 2011 in one of the sugar factories a robot with its' working head hit a pallet full of sacks, as result of the operator's mistake. Damage appeared not only in the head, but also a serious breakdown of the robot occurred (one of the robot's arms was broken and another one fractured). The damaged robot with its working head is shown in Fig. 1. Such a serious breakdown during a sugar campaign is a serious problem, as the production line cannot have long-lasting shutdown. A repair of the working head is not simple, but it is cheap enough and relatively quick. The robot's breakdown is incomparably more expensive, it needs highly skilled crew and usually long delivery time of spare parts. From that practical point of view, i.e. issues of a concrete plant, the reliability of production line, understood as a probability of the above described collision and a minimization of its negative effects is certainly an important matter. The minimization of negative effects means costs of repairs and the time spent for complete reconditioning of the production line.

The paper treats of minimization of negative effects of such events by introducing in the working head's structure special zones able to absorb large energy and impact. Particularly dangerous are these impact events, in which the compliance of the working head's operating elements cannot be exploited and in result the impact is transferred in its major part to the head's arm and farther to the robot's wrist. In many palletization heads the frame is bipartite with both parts joined by compliant elements. However, such structural solution not always can absorb the destructive energy and – on the other hand often renders it difficult to gain sufficient stiffness of the frame.

The current paper is a study of some engineering conception and precedes the planned laboratory experiment, as well as practical application. It is concentrated on some case of a thin-walled column with dimples, which could later serve as an energy absorber in working heads of robotized production lines, but also in other applications, where the thin-walled structure is expected to absorb large energy. Introduction of the dimples had in target to make the column more compliant, ordering of the structure's destruction process, such that the element underwent the concertina folding and thus saved the damage sensitive parts of the equipment from destruction. This would

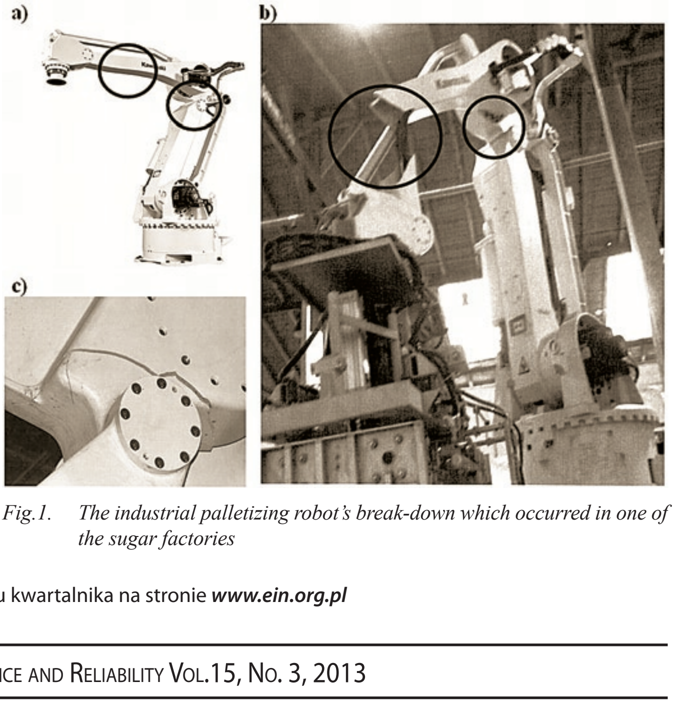

Fig.1. The industrial palletizing robot's break-down which occurred in one of the sugar factories

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(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** naturally reduce the total cost of repairs and the time of shutdown after the break-down.

In the paper an influence of the global initial deflections (the initial curvature of the column's axis) on subcritical form of the equilibrium path was examined. The meaning of these analyses consists in an assessment of the structure's sensitivity to a deviation of its axis from its ideal shape. A possibility of performing by the absorber its function even when it underwent meaningful deviation was also tested. Reliable results were gained for very large deformation. A comparison was performed of the behaviour of the columns with dimples and those with smooth walls in the aspect of their ability to absorb the impact energy.

The subject of the limit load-carrying ability of isotropic columns with square cross-section has been well recognized so far. However, there is a considerable lack of papers on practical applications of the above described phenomena. Many articles depict experimental tests of such structures, for example [8,9,16,17]. Abramowicz [1,2] dealt with steel columns, among others, in the aspect of their application as energy absorbers. In the works [18,19] Teter considered a phenomenon of interactive buckling of analogous structures within a static and a dynamic regime. The works of Langseth and Hopperstad [10, 11] concentrated on the columns made of aluminium. Meng and Wierzbicki [13, 20, 21] analysed failure mechanisms of closed cross-section columns. However, no articles concerning columns with corners shaped as described above (with dimples) were found in the open literature. Even though in [12, 14] the authors studied the behaviour of tubular columns with dimples, these flaws were treated as damage and each column had only one dimple at a time. This allows to presume, that the presented study of a thin-walled structure can be considered as unique.

2. Object of research. A model of column with dimples

The object of the analysis was a model of the hollow column with a square cross-section □68x1 made of aluminium alloy EN AW6060-T6 (R_e=175 MPa, R_m=250 MPa, ν=0.33). This material exhibits linear hardening during plastic flow (E=70000MPa, E_t=937,5MPa). The column's height was assumed to be six times greater than its average cross-section dimension l=6x67=402 mm. The analysis of buckling modes of a smooth column (without dimples) yielded a location of nodal line for the first mode. This allowed to place the corner dimples properly. The process of modelling of the column with dimples was realized with the Catia v. 5 software package in the Generative Shape Design module. The model of the column with a magnified corner dimple is presented in Fig. 2.

The dimple's geometry was characterized by the main radius R=30 mm, whereas its surface passed into the column's wall with another radius r=6 mm. The depth of the dimple was 6.7 mm, what equalled 10 % of its width. As it is shown in Fig. 2, quads of dimples were made at five levels every 67 mm. A surface model elaborated in the Catia v. 5 software was fully parameterized. Thus, the location and the geometry of the dimples could be modified very easily.

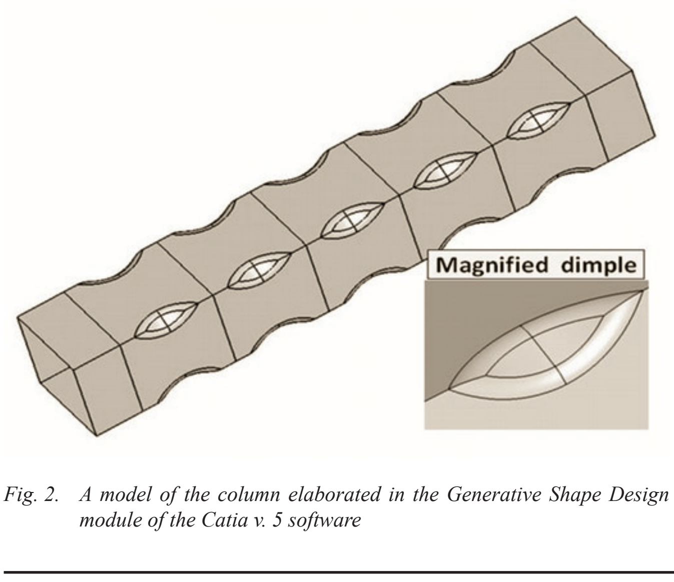

Fig. 2. A model of the column elaborated in the Generative Shape Design module of the Catia v. 5 software

The model of the column was subsequently imported to the ABAQUS software environment in order to perform the Finite Element Analysis (FEA) [3]. The analysis was performed in three stages:

1. An analysis of the buckling eigenmodes of the column with dimples, calculations of the critical force,
2. An elaboration of the column's models with some global initial deflection (initial curvature of the axis); the models differed among each other with an amplitude of the initial deflection (from 0 to 5 mm every 0.5 mm);
3. Performing a static nonlinear analysis with many variants of compressed column with dimples.

The way of modelling of the phenomena taking place in the compressed columns did not differ from some procedures presented in [4, 6]. Similar multi-stage way of modelling was shown in [5, 7, 15].

In all stages the same boundary conditions, as well as loading conditions were applied. Due to the fact, that in the planned experiments the real columns will be loaded through the existing grips with articulated support and that the current paper is a pre-experimental study, a special care is taken about a conformity of the real and the numerical boundary conditions. In the FEA model two reference points RP1 and RP2 were established and by the "Coupling" type constraints the column's boundaries were fixed to them in stiff. The reference points were located at h=65 mm from the column's boundaries, what referred to a distance between an articulated joint sphere's centre and the grip's bearing surface. In the RP1 point the structure was devoid of the three translational degrees of freedom and the rotational degree of freedom around the Z axis. In the RP2 point, in which a concentrated load was applied, the boundary conditions were changed only by enabling translations along the Z axis, in comparison with the RP1.

In Fig 3 the ABAQUS model of the column with the applied boundary and loading conditions is presented.

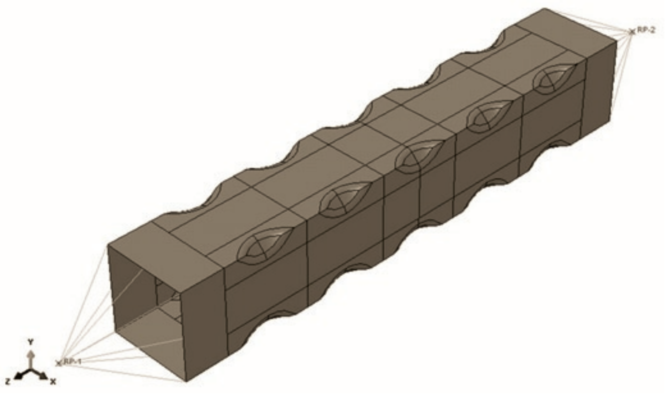

Fig. 3. The ABAQUS model of the column with applied boundary conditions

At the first stage of the analysis special attention was paid to obtain an optimal FEA mesh, i.e. dense enough in significant areas and generally regular. It was very important to evade any influence of the mesh quality on simulation results, as at subsequent stages still the same mesh was used. In Fig. 4 the model of the column with the FEA mesh was presented. It is well visible, that the areas, where the mesh is regular, made of the S4R 4-noded shell elements with reduced integration prevail in the model. However, in the vicinity of the dimples the S3 3-noded elements appear, even though the 4-noded elements still dominate there.

Before performing the analysis it was necessary to add in the input file a routine enabling introduction of the profile's shape deformation

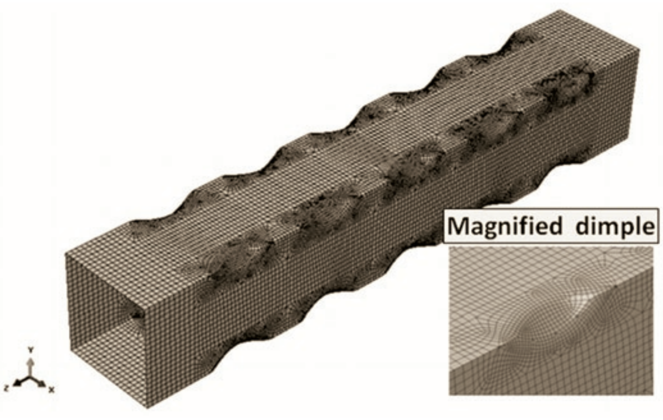

Fig. 4. The ABAQUS model of the column after the FEA mesh generation

by calling a file with a "fil" extension. The final effect of the first stage was finding the critical force, as well as the buckling modes. These data in the form of file were exploited in a subsequent stage of modelling. In Fig. 5 the first and the second buckling mode together with the respective critical force values are displayed.

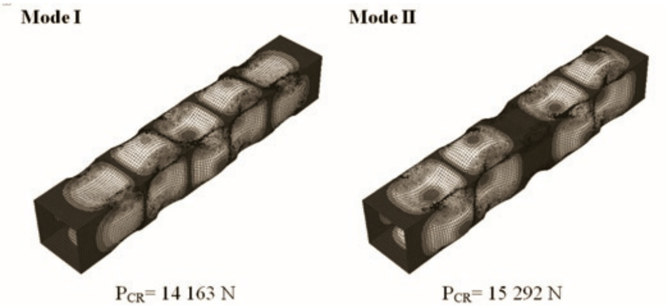

Fig. 5. The first and the second buckling mode of the profile and the respective values of critical forces

The second stage of building the model had in target getting the column's shape allowing for two kinds of perturbations: small initial deflection of the whole profile and geometrical imperfections imitating the first buckling mode. The global initial deflection (corresponding to the primordial curvature of the symmetry axis) of the column was obtained by the displacement method. Namely, the displacement along the x axis of the central cross-section of the column was declared. Fig. 6 shows the column's model with the assumed displacement. A set of models with the initial deflection being a multiple of 0.5 mm within the range of 0 to 5 mm was elaborated.

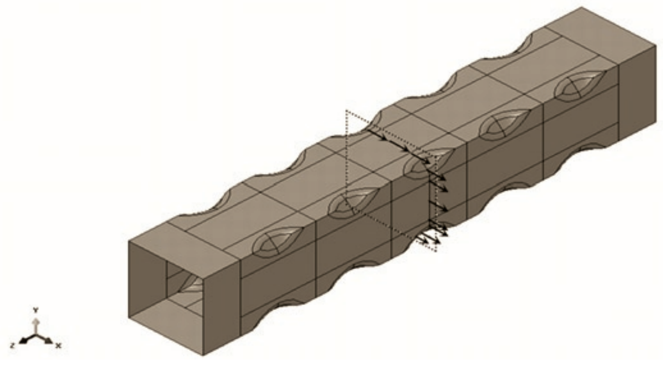

Fig. 6. The column's model with the declared displacement of the central cross-section

The way of getting perturbations of the column's shape with geometrical imperfections was based (as mentioned above) on adding in the ABAQUS job input file the routine downloading the geometry definition from the appropriate "*.fil" file. In the routine a consecutive mode number, as well as the imperfection's magnitude in millimetres had to be determined. The result of the second stage was the shape of the column distorted by the global deflection and the imperfection. After running the analysis the deformed column was brought into a particular stress state. For the purpose of obtaining a stress-free form of the structure it was necessary to import the model into the ABAQUS environment once again. The model had to be read as a "Part" from an appropriate "*.odb" database file.

At the third stage the model had no geometry, but the deformed FEA mesh. In order to conduct any computations on such a column the whole process of the model preparation had to be started from the beginning, excluding only the FEA mesh generation. The obtained distorted model of the column with the applied boundary conditions and the load is shown in Fig. 7.

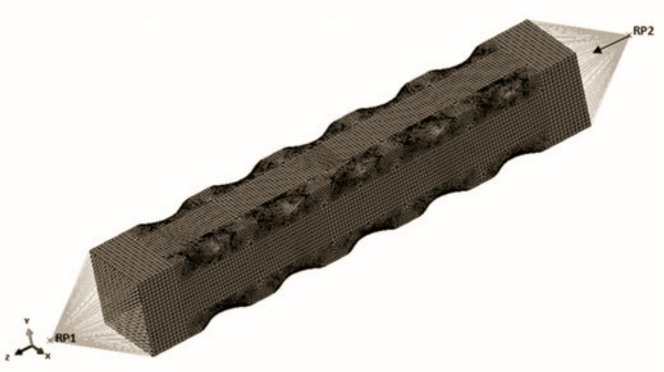

Fig. 7. The ABAQUS model of the column with distorted FEA mesh, applied load and boundary conditions

In result of the first and the second stage of modelling a set of 10 models of the columns varying in the amplitude of initial deflection was obtained. The models were designated by the symbols from A00 to A50, where the number stands for the amplitude of initial deflection multiplied by 10.

The column was loaded with a force P= 25 kN and subjected to the analysis, taking into account geometrical and material nonlinearities. The FEA model allowed for contact phenomena, both at internal and external surfaces. The specificity of the nonlinear analysis extorted, that the column was loaded incrementally and in the first step the load equalled 0.05P. In order to gain the nonlinear equilibrium path in as wide range as possible, a stabilization was introduced in the iterative method by declaring damping of energy at the level of 0.02% (an appropriate damping factor was specified).

3. Results

The analysis of the deformation process of column's models differing among each other with the amplitude of initial deflection lead to interesting conclusions. In case of the columns with the initial deflection amplitude from 0 to 2 mm the absorber's damage process started from the middle cross-section and propagated subsequently to the upper levels, in order to move in the final stage to the lower zone. It can be seen in Fig. 8, where the modes of deformation of the columns at the beginning and in the end of the process are shown. In the columns characterized by the initial deflection amplitude from 2.5 to 5 mm the absorber's damage process started in a cross-section above the middle one and the subsequent destruction ran similarly. It is shown in Fig. 9, where the modes of the columns' deformation at the beginning and in the end of the process are shown. It is visible, that at relatively large deviations from the ideal column's axis the simulation of the nonlinear structure's crushing process did not reach its end (even though the software package made ca. 1000 of iterations).

As numerical simulation of the crushing is a strongly nonlinear process, both in the material properties' and in the geometrical sense, with contact phenomena taken into account, the obtained results should be considered as a success, because they show the course of the absorber's destruction within a wide range of its functioning. An ideal would be gaining the effect of the column's concertina folding, what means absorbing maximal possible amount of energy. In practical applications the amount of absorbed energy depends, however, on some external factors and it might turn out, that the columns would never be exposed to such a high loads.

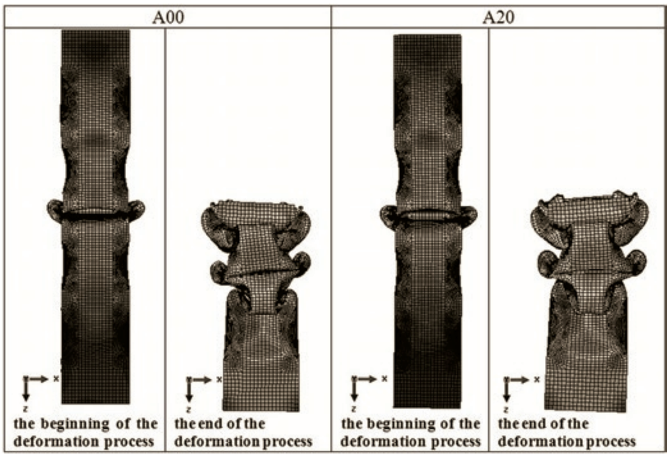

Fig. 8. Modes of deformation of the columns No. A00 and A2

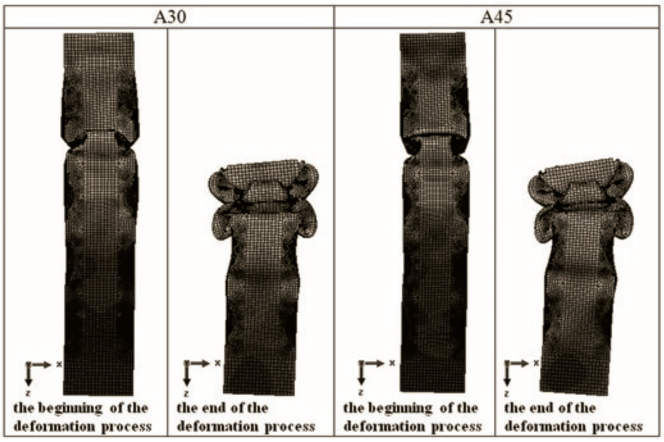

Fig. 9. Modes of deformation of the columns No. A30 and A45

Fig. 10 presents a relation between the load RF3 (the reaction force along the Z axis) and the column's shortening U3. The plot shows the absorber's crushing process associated with the energy absorption. The specific peaks of the curves depict the crushing of subsequent levels of the columns. Similar curves can be found in many works treating of experimental results, among others [7, 8, 15, 16]. When the load increased together with the column's shortening then the stress increased, as well. A decrease in the reaction force value RF3 together with the increase in the column's shortening was associated with the plastic flow of the subsequent levels.

The numerical simulation succeeded to reach large deformations. The columns shortened by 185mm to 230 mm, depending on the column's type, what was, taking into account its initial length equal 402 mm, from 46% to 57%. One can see, that the operating mode of the structure at the stage of its crushing is similar, apart from the column's model. In spite of this resemblance, at the shortening U3 equal approximately 70 mm, the following groups of models: A00 A20 and A25 A50 started to diversify. In the second group (having the amplitude of initial deflection equal to 2.5 5 mm), a specific plateau appeared; it was associated with the structure's shortening within the range of 70.7 to 91.6 mm. A penetrating observation of this fact indicates, that the respective fragment of the characteristic curve is related to the local deformation of the column in the vicinity of its support, as shown in Fig. 11. The occurrence of such perturbations in so strongly nonlinear process, does not change the overall character of the plots, in which the subsequent peaks depict the deformation of consecutive levels.

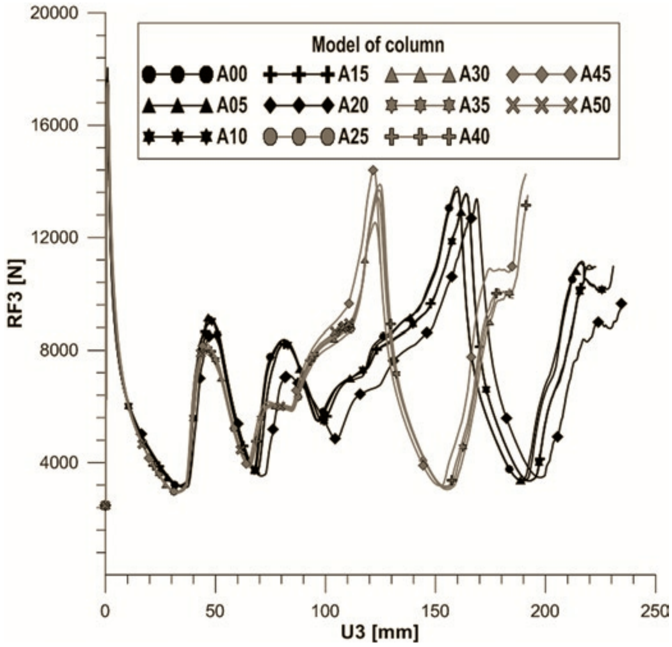

Fig. 10. The reaction force RF3 vs. the column's shortening U3 for the models of the columns differing with the amplitude of initial deflection

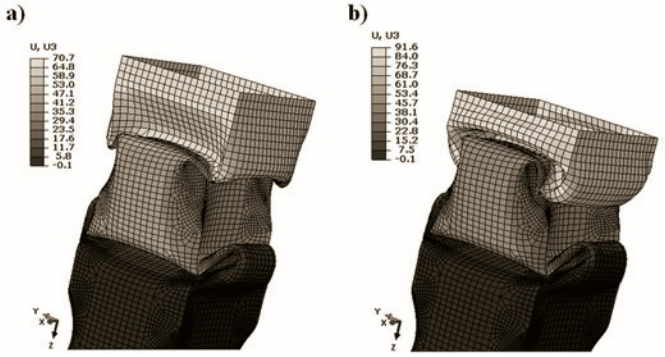

Fig. 11. Operation of the structure in the plateau phase

4. Comparison of the new solution with the classical column

Advantages of the new solution become visible, when one compares the behaviour of the columns with dimples and those with smooth walls. The models were elaborated and numerically analysed for the whole family of columns without dimples. The models had identical boundary conditions and differed besides their shape only with the load, which equalled P=28 kN. However this had no practical meaning due to the fact, that the load was applied stepwise. The way of models' designation was analogous as for those with dimples, i.e. G00 G50.

The course of the deformation process of the smooth columns at the initial deflection's amplitude not exceeding 1.5 mm was very close to that of the dimpled columns, what can be seen in Fig. 12.

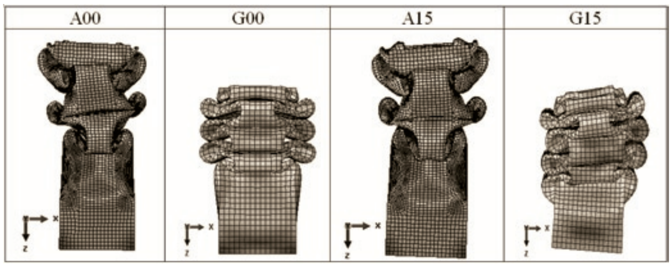

Fig. 12. Modes of deformation of the columns with dimples in comparison to the columns with smooth walls at the amplitude of initial deflection equal 0 – 15 mm

However, with the increase of the initial deflection amplitude a considerable difference in the course of the structure's deformation process occurred. It is superbly visible in Fig. 13, where the mode of the dimpled absorber's structure deformation practically does not depend on the initial deflection's amplitude. The columns with smooth walls "did not want to" make the concertina folding together with the increase of the initial deflection's amplitude, but they rather broke, what very adversely influenced the amount of absorbed energy and in consequence the reliability and the functionality of this type of structure operating as a specific protector.

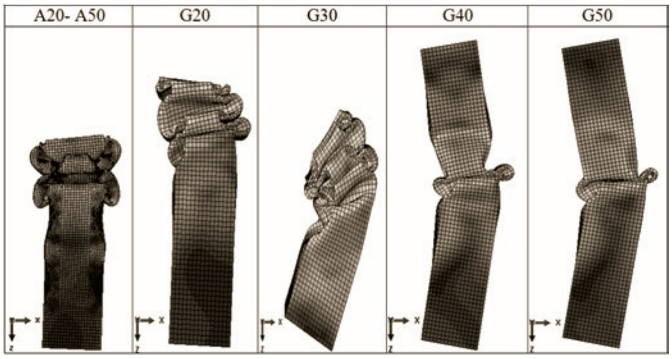

Fig. 13. Modes of deformation of the columns with dimples in comparison with the columns with smooth walls at the amplitude of initial deflection equal 20 – 50 mm.

Fig. 14 presents a plot of operation of the column with dimples and the one with smooth walls for the models of structures with ideally straight axes. In the magnification box one can see, that the model with dimples started to operate, i.e. to absorb the energy under the load ca. 23% lower than the smooth column. In case of an impact loading the former structure would react earlier, thus protecting the machinery against damage.

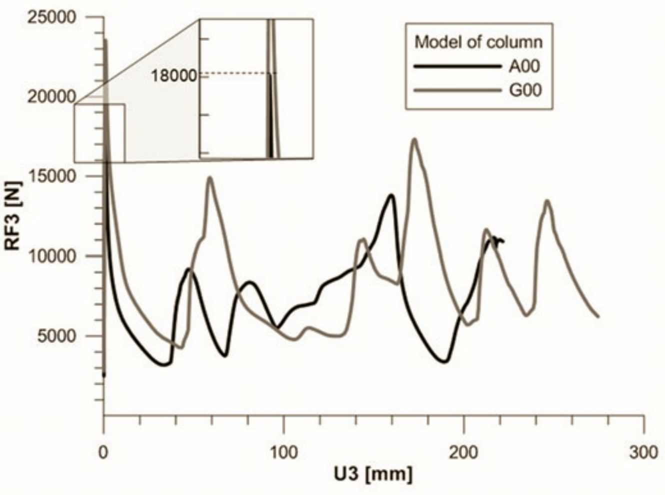

Fig. 14. Reaction RF3 vs. shortening U3 for the models of columns with dimples and with smooth walls (straight axis).

5. Conclusions

The structural solution presented in the paper is currently at the stage of numerical analyses. It exhibits a big potential to be applied as an absorber. In comparison with classical solution it shows an exceptional resistance to any perturbations in the form of some initial curvature, which can yield from manufacturing errors or from the fact, that the structure experienced deviation as a result of collision etc. In the areas of the dimples the plasticization appeared at the earliest and the structure in some sense compensated deviations from its original shape. Subsequent numerical research is needed in order to assess an influence of the dimples' lay-out and their geometry on the structure's behaviour. The research would have in target finding optimal solutions in respect of the structure's ability to absorb the energy. The main goal would be gaining high degree of deformation at an adequate load, such that the absorber had appropriate characteristics. The next stage would be experimental verification of the numerical model and an implementation of the elaborated solutions in a specific industrial machinery.

References

1. Abramowicz W. Thin-walled structures as impact energy absorbers. Thin Walled Structures 2003; 41: 91–109.
2. Abramowicz W, Jones N. Dynamic Axial Crushing of Square Tubes. International Journal of Impact Engineering 1984; 2: 179–208.
3. Abaqus HTML Documentation.
4. Arbocz J. Post-buckling behaviour of structures. Numerical techniques for more complicated structures. Lecture Notes In Physics, 228, 1985
5. Bieniaś J, Dębski H, Surowska B, Sadowski T. Analysis of microstructure damage in carbon/epoxy composites using FEM, Computational Materials Science 2012; 64: 168–172.
6. Doyle FJ. Nolinear analisys of thin- walled structures. New York: Springer-Verlag, 2001.
7. Dębski H, Koszałka G, Ferdynus M. Application of FEM in the analysis of the structure of a trailer supporting frame with variable operation parameters. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (2): 107–113.
8. Hambly ET, Calladine CR. Buckling Experiments on damaged Cylindrical Shells. International Journal of Solids and Structures 1996; 33 (24): 3539–3548.
9. Hamouda AMS, Saied RO, Shuaeib FM. Energy absorption of square tubular structures. Journal of Achievements in Materials and Manufacturing Engineering 2007; 24: 36–42.
10. Langseth M, Hopperstad OS, Hanssen AG. Crash Behaviour of Thin-Walled Aluminium Members. Thin Walled Structures 1998; 32:127–150.
11. Langseth M, Hopperstad OS. Static and Dynamic Axial Crushing of Square Thin-Walled Aluminium Extrusions. International Journal of Impact Engineering 1996; 18 :949–968.
12. Lancaster ER, Palmer SC. Model Testing of Mechanically Damaged Pipes Containing Dents and Gouges. ASME Pressure Vessels & Piping Conference New York 1992; 235:143–148.

13. Meng Q, Al Hassani STS, Soden PD. Axial crushing od square tubes. International Journal of Mechanical Science 1983; 25: 747–773
14. Ronalds BF, Dowling PJ. Buckling of Inpact and Damaged Offshore Shell Structures in: Advanced Marine Structures, C.S. Smith and J.D. Clarke. Eds. Elsevier Applied Science, London 1987: 201–218.
15. Rudawska A, Dębski H. Ocena wytrzymałości połączeń klejowych ze stopu aluminium z wykorzystaniem analizy numerycznej MES. Eksploatacja i Niezawodnosc- Maintenance and Reliability 2011; 1 (49): 4–10.
16. Singer J, Arbocz J, Weller T, Buckling Experiments. Experimental methods in buckling of thin-walled structure. Basic concepts, columns, beams, and plates, Volume 1, John Wiley & Sons Inc. New York 1998.
17. Singer J, Arbocz J, Weller T, Buckling Experiments. Experimental methods in buckling of thin-walled structure. Shells built-up structures, composites and additional topics. Volume 2. New York: John Wiley & Sons Inc, 2002.
18. Teter A, Kolakowski Z. Interactive buckling and load carrying capacity of thin-walled beam-columns with intermediate stiffeners. Thin Walled Structures 2004; 42(2):211–254.
19. Teter A. Static and dynamic interactive buckling of isotropic thin-walled closed columns with variable thickness. Thin Walled Structures 2007; 45(10-11):936–940.
20. Wierzbicki T, Huang J. Initiation of plastic folding mechanism incrusched box columns. Thin Walled Structures 1991;13: 115–143.
21. Wierzbicki T, Abramowicz W. On the Crushing Mechanics of Thin-Walled Structures. ASME Journal of Applied Mechanics 1983; 50: 727–734.

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