VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

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MODELLING DEFORMATION BEHAVIOUR AND FRACTURE OF A DIAPHRAGM OF THE GAS SHOCK TUBE

Summary of Doctoral Dissertation
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VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

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DIAFRAGMOS SMŪGINIAME DUJŲ VAMZDYJE DEFORMAVIMO IR IRIMO MODELIAVIMAS

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Technologijos mokslai, mechanikos inžinerija (09T)

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GENERAL CHARACTERISTIC OF THE DISSERTATION

Research area and topicality of the work. The gas shock tube is the most popular device used to get shock waves. Shock tubes are applied to various scientific investigations in aerodynamics and metrology. In the last decades shock tube has been used in chemistry, medicine and other branches of science.

One of the most important functional elements of the tube is a diaphragm; which divides the tube in to two high and low pressure compartments. The device is operated by rupturing the diaphragm, thus rapidly releasing the compressed gas to flow along the tube and form a shock wave. Actually, the most important characteristics of the shock wave depend on many factors including the geometry of the tube, the diaphragm design, properties of the gas used, etc. It has been proved that the elastic-plastic fracture of the diaphragm is the most significant factor, which determines the dynamic behaviour and characteristics of the shock wave.

Recently, the significant progress in numerical methods and computational technologies has provided a basis for solving complicated physical problems. The progress in modelling in last decades seems to be useful for the development of realistic simulation tools for simulating the fracture of shock tube diaphragm.

It may be stated that knowledge-based design of the diaphragm, relying on the results of numerical simulation, is being constantly improved.

Aim and tasks of the work. The main aim of the work is to describe and investigate numerically the deformation and fracture processes of the diaphragms, as well as investigating the influence of the incision depth on diaphragm opening and giving recommendations concerning the control of the opening process.

To achieve this aim, the following tasks were set:

1. To investigate experimentally the deformation and fracture of diaphragms.
2. To investigate numerically the deformation and fracture of the diaphragms with and without incisions.
3. To investigate the influence of the geometry of incision on deformation and fracture.

Research objects and methods. The finite element method was elaborated to investigate numerically the nonlinear elastic – plastic deformation behaviour and fracture of the shock tube diaphragm with cross incisions. Experiments were performed to validate the numerical results.

Scientific novelty and originality. Deformation and fracture behaviour of the slender diaphragm with cross incisions is simulated by the developed finite element model.

The influence of incisions geometry on the critical pressure of diaphragms was examined by applying deformation and fracture criteria.

Original experiments of diaphragms with incisions were performed.

Theoretical and practical value. The developed computational model serves as the basis for numerical prediction of load capacity, deformation behaviour, location and spreading of plastic deformation zones and for a description of fracture.

Based on simulation results, the recommendations considering diaphragm material and incisions geometry may be provided.

Acknowledgment. Dissertation has been prepared at the Department of Strength of Materials of Vilnius Gediminas Technical University in cooperation witch High Power Pulse laboratory of Vilnius Semiconductor Physics Institute. I am very grateful to the scientific advisor Prof Dr Habil R. Kačianauskas and to the consultant Assoc Prof Dr Č. Šimkevičius and to the colleagues of the Department of Strength of Materials and High Power Pulse laboratory for consulting and assistance in performing the experimental research.

Approbation and publications. The main results of the dissertation were presented at 7 scientific conferences. Three scientific papers were published on the topic of dissertation. One of them was included in the proceedings of the conference organized by international scientific organizations (ISI Proceedings), while the other were published in the reviewed periodical included in the databases from the list approved by Lithuanian Scientific Council in 2006.

The structure of the scientific work. The thesis is written in Lithuanian. It consists of the introduction, five chapters, conclusions and the list of references (106 items). The dissertation comprises 88 pages, 69 pictures and 4 tables.

Chapter 1. Shock tube

The shock tube (Fig 1) is made of a solid smooth wall pipe of circular cross - section divided into two compartments separated by a thin diaphragm.

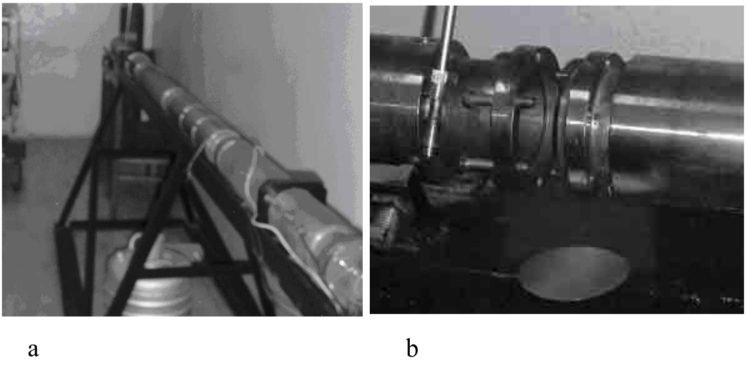


Fig 1. Gas shock tube (a) with diaphragm section fragment (b)

The device is operated by bursting the diaphragm, thus rapidly releasing the compressed gas to flow along the low pressure channel. Initially, the gas pressure in one compartment of the tube is much higher than that in the other. The high pressure compartment chamber contains the drive gas, while the low pressure compartment channel has the working gas. When the pressure in the high pressure compartment is increased up to a critical point, the diaphragm is fractured and the high pressure gas suddenly expands into the low pressure compartment, thereby creating a shock wave, which travels faster than the expanding gas.

Two basic mechanical fracture initiation mechanisms are used in experimental practice. A brittle fracture is described by Sasoh et al. Another construction based on ductile fracture of a diaphragm with cross - section incision is described by Volkov and Stankevič in their experimental studies.

In the last decades researchers simulated numerically the fracture of brittle diaphragms and thin and thick diaphragms made of metal without incision, as well as diaphragms made of extremely light and thin materials such as cellophane or mylar. Due to high complexity, different fracture models may be used to reproduce distinct fracture processes of these diaphragms.

The shock tube, considered in the present investigation, is a device for determining major dynamical characteristics of the sensors used in Semiconductor Physics Institute of Vilnius.

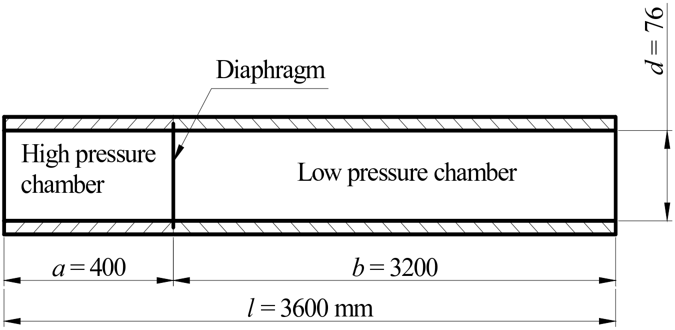


Fig 2. A schematic view of the shock tube

The main characteristics of the shock tube (Fig 2) are as follows: length l = 3600 mm, internal diameter of the tube d = 76 mm, pressure p reaching 100 bars, and a particular drive gas – argon or helium.

Chapter 2. The numerical model of the diaphragm

The shock tube diaphragm considered presents a very thin circular plate of relative thickness $\bar{t} = t_d/d_d = 1/127$. Since $\bar{t} < 1/100$, then, the second-order theory should, generally, be applied to mechanical analysis. The cross – section of the diaphragm structure with supports and active uniform pressure p and the main geometric characteristics is illustrated in Fig 3.

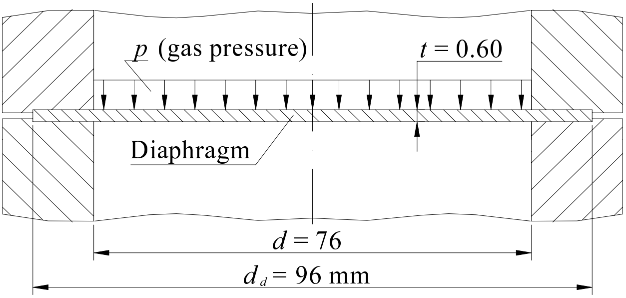


Fig 3. Cross section of the diaphragm

Due to axial symmetry of geometry and loading, the diaphragm can be considered as an axisymmetric solid (Fig 4) problem.

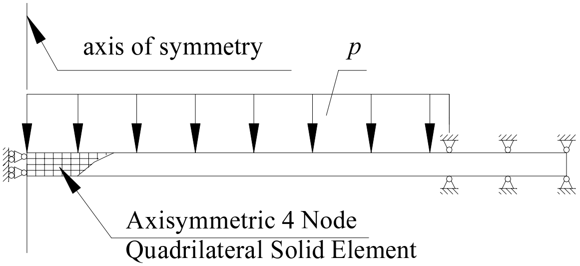


Fig 4. 2D finite elements model

Geometric boundary conditions restricting radial displacements are given on the central line (Fig 4), while the support contour is modelled as clamped in the structure. The structure is loaded by applying the uniform and symmetric pressure of a conservative character, which is, generally, time (*T*) – dependent function $p = p(T)$.

Various types of FE models were investigated. The 2D finite element model was generated by a rectangular structured mesh using the first order four node elements, as it is usually recommended for non - linear analysis. The element has plasticity, large deflection, and large strain capabilities. The ANSYS code is used for the analysis.

To capture local effects in the vicinity of incisions the, 3D model was developed.

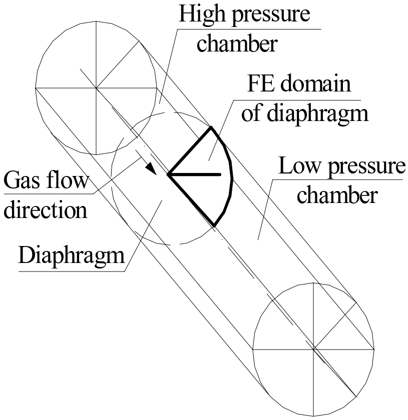


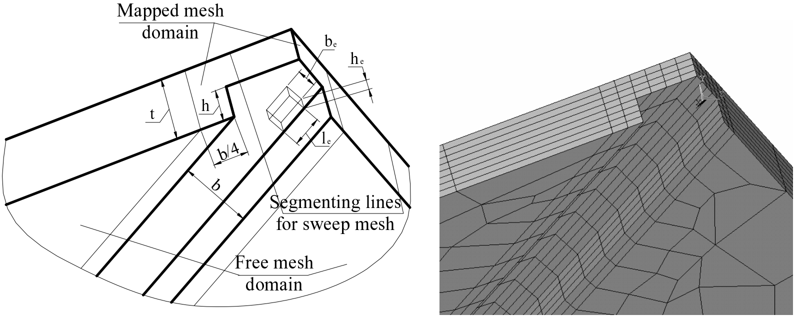
Fig 5. A schematic view of the shock tube with FE domain of the diaphragm

The diaphragm structure has double axial in-plane symmetry; therefore, only a quarter of it is considered as a three-dimensional finite element domain (Fig 5). The brick element, which is used in modelling and analysis of diaphragms by finite elements, has plasticity as well as large deflection and strain capabilities.

Two types of 3D meshing techniques have been explored for modelling the plate as a 3D body. The mapped mesh may be considered as a regular mesh. It has a characteristic mesh dimension l_e applied for discretization in the vicinity of defect. It has been observed that mapped meshing is highly inefficient because a realistic model with 8 layers dramatically increases the number of DOF.

The second-type meshes present swept or irregular meshes. These meshes are defined by two characteristic in-plane dimensions: the element length in the vicinity of defect l_e and the element length in the boundary l_{eb}. It is computationally favourably, however, implementation of irregular disconnecting of elements would be problematic.

For the purposes of fracture analysis, the combined three-dimensional finite element meshing technique comprising structured mesh in the vicinity of the initiated defect and free in-plane mesh was modified and further developed. In the frame of this approach, the diaphragm was considered as a three-dimensional multilayered plate. The governing parameter of the discretization is thickness of individual layer h_e (Fig 6 a). This parameter is, actually, the thickness of a 3D brick element. It is defined as a fraction of the plate thickness t and the variable defect depth h. The detailed geometry of the defect is presented in Fig 6 b.



a

b

Fig 6. Geometry of the incision (a) and his discretization (b)

The remaining part is covered by the unstructured in plane mesh, the density of which is defined by a characteristic dimension of the element length l_{eb} at the boundary line. The example of the mesh fragment (Fig 6) illustrates meshing concept of the defect area.

Finally, the above-discussed meshing was adopted for generation of variable depth of incision and, later, for automatic generation of rupturing elements.

The FE model applied in prefracture analysis was modified for describing fracture behaviour. Disconnection of material is implemented through the one-dimension connection element (Fig 7).

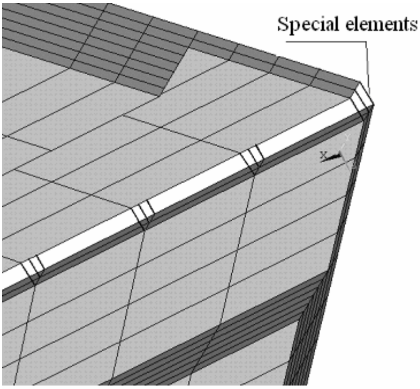


Fig 7. Mesh fragment with special fracture elements

Application of special fracture elements is one of the tools used in fracture mechanics, where crack propagation path is known in advance. Disappearing elements are small enough and do not violate energy balance.

Chapter 3. Experimental investigations

The main object of experiments was evaluation of the material properties of the diaphragm, investigation of diaphragm's deformation behaviour and opening processes.

The material of the diaphragms is copper. It is assumed to be homogeneous and isotropic and its mechanical characteristics are obtained experimentally. Finally, the behaviour of copper used for diaphragms is described by the non - linear stress (σ) strain (ε) diagram (Fig 8), experimentally evaluated from the tensile tests. These tests were performed in the Laboratory of Strength Mechanics of Vilnius Gediminas Technical University according to the standard EN 10002.

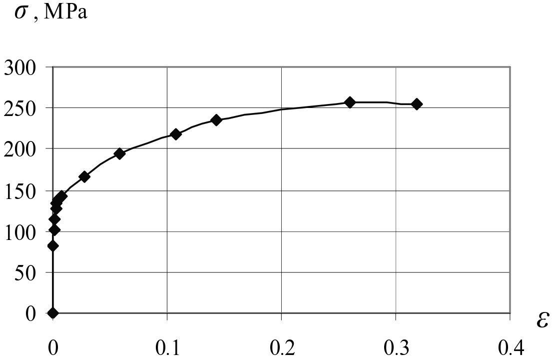


Fig 8. Tension test of diaphragm material

Two types of unique experiments aimed at determining the deformation and fracture of diaphragms were performed in Semiconductor Physics Institute.

The main goal of the experiments with diaphragms without incisions is to observe the deformation effects under static pressure. The experiment was conducted with the shock tube having the following parameters: maximum pressure in high pressure chamber was p = 2.0 MPa; the drive gas was helium; the working gas was air. The pressure in high pressure chamber was slowly increased up to the maximum value for about 100–120 seconds, therefore, the process of deformation was static. Then, the pressure in the high pressure chamber was reduced. The view of the diaphragm after the experiment was over is shown in Fig 9.

Fig 9. Shock tube diaphragm under deformation

The measured value of residual deflection w at the central point of the diaphragm was 7.40 mm.

The experiment with diaphragms with cross incisions was performed under the following conditions: maximum pressure in high pressure chamber p = 8.66 MPa. The experimental procedure was similar to the described above.

The view of the diaphragm after the experiment was over is shown in Fig 10.

Fig 10. Diaphragm with incisions under deformation

The measured value of residual central deflection w of the diaphragms with incisions was 5.00 mm.

The pressure loading was quasistatic, while the loading pressure velocity was slow and equal 0.46 MPa/s. The value critical pressure was obtained.

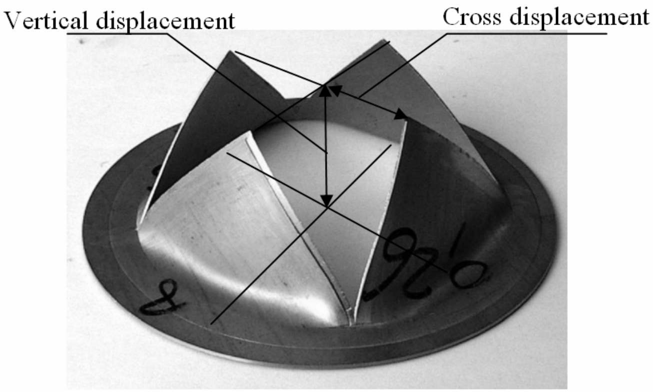


Fig 11. Diaphragm after fracture

The fracture experiments were performed with diaphragms having incisions depth equal to 0.15, 0.30 and 0.45 mm. The measured values of vertical displacements (Fig 11) were 29.8 mm for diaphragm with 0.30 mm incisions depth and 23.2 mm for diaphragm with 0.45 mm incisions depth.

Chapter 4. Prefracture deformation behaviour

The prefracture deformation of the diaphragm with the initiated incisions is formulated as problem non-conservative, geometrical and physically nonlinear analysis. The purpose of this chapter is to investigate prefracture behaviour of diaphragms with different defect depths for diaphragms with defect characteristics. Three models, having the values of the defect depth equal to $h = 0.25t$, $h = 0.50t$ and $h = 0.75t$, were investigated, and the results were compared with a plate with zero defect.

Numerically obtained pressure-central deflection curves are presented in Fig 12. The last curve with $h = 0.75t$ demonstrates the limit behaviour of the diaphragm, where maximum pressure value $p = 0.398$ MPa may be considered to be the limit pressure. This pressure corresponds to the opening of the diaphragm.

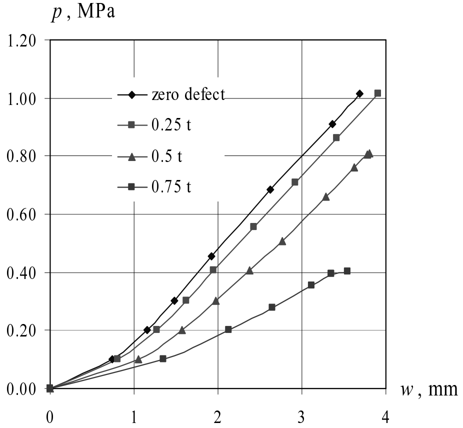


Fig 12. Deflection curves of the central point

Examination of the influence of the defect has shown that the increase of defect depth by 25 %, 50 % and 75 % at the same pressure increases deflections of diaphragms by 1.67, 2.18 and 2.31 times.

Distribution of plastic strains obtained according to von Mises strain is given in Fig 13. The numerical results indicate the development of the local plastic zones characterizing the diaphragm behaviour. The main plastic zone occurs in the area at the centre of the plate and propagates along this area. The second plastic zone is concentrated along the clamped boundary, which corresponds to the occurrence of a circular plastic hinge. This proves the necessity of using the suggested locally concentrated mesh concept.

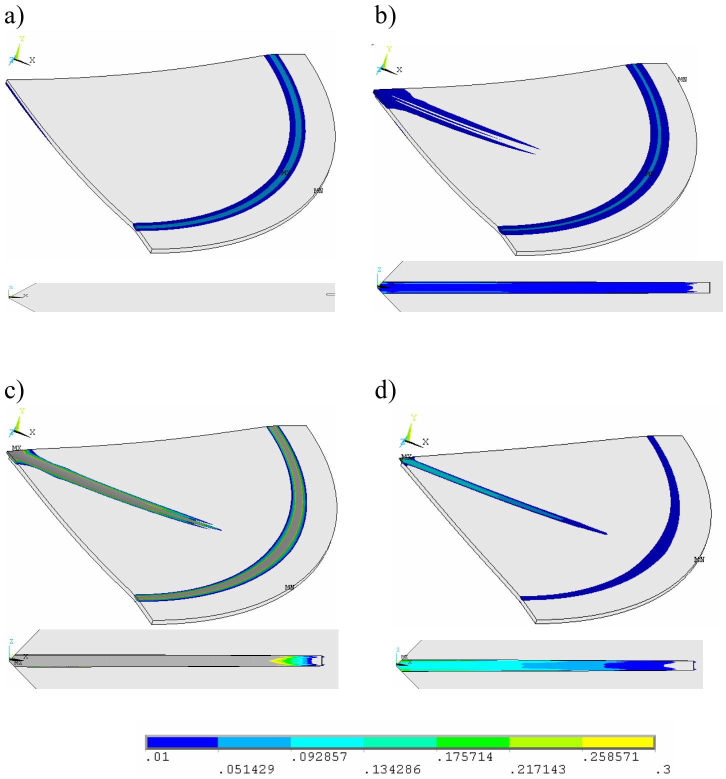


Fig 13. Distribution of plastic strains in diaphragms of various incision depth: a) zero defect; b) $0.25t$; c) $0.50t$; d) $0.75t$

The quantitative examination of the strains indicates that the maximum value could be found in the centre of the diaphragm. Their absolute values and relative values compared to the clamped boundary increase with the increase of the defect depth.

The results described in this chapter explain the experimental facts that fracture of the diaphragms with smaller defects occasionally yields an undesired irregular fracture pattern of the diaphragm in the contour.

Chapter 5. Simulation of fracture

The deformation behaviour of the diaphragm during fracture is, generally, a complicated process, involving not only geometrical and physical but structural non-linearity as well. The detailed mathematical model depends, however, on the specified properties of the diaphragm and the incision.

A recent approach assumes fracture to occur under proportionally increasing quasistatic pressure. This assumption gives overestimated deflection values, however, coupled behaviour of gas flow and structure may be considered a future challenge. Moreover it is expected that the rate of loading is lower compared to the deformation rate during fracture. The problem is solved incrementally by controlling the pressure, while the solution is highly sensitive to the structure's pattern.

Deformation behaviour during opening may be characterized by considering development of plastic strains. Distribution of plastic strains of diaphragms with 75 % incisions depth obtained according to von Misses strain is given in Fig. 14.

The plastic zone, which occurred at the crack tip propagates towards the support and touches another zone. Finally, the plastic strains are concentrated in the vicinity of the clamped boundary.

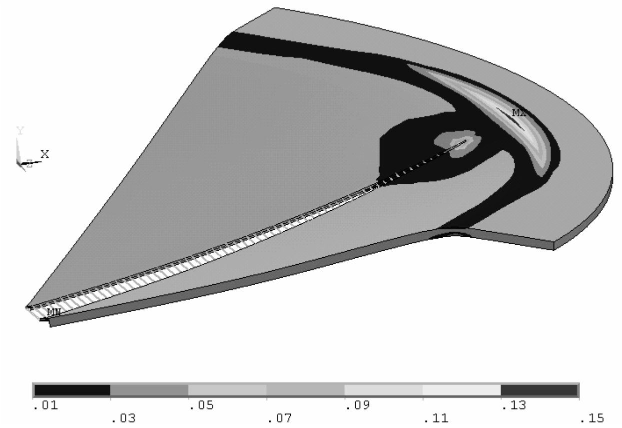


Fig 14. Distribution of plastic strains in fracture model

A schematic view of the deformed diaphragm after fracture is shown in Fig 15.

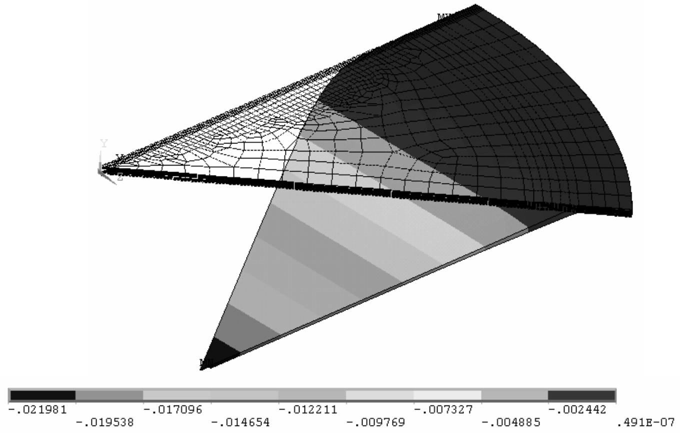


Fig 15. Fractured numerical diaphragm

The fracture phenomena may be illustrated by the opening displacement along the axis of the central point of diaphragms dramatically increases after the fracture of special elements (Fig 16).

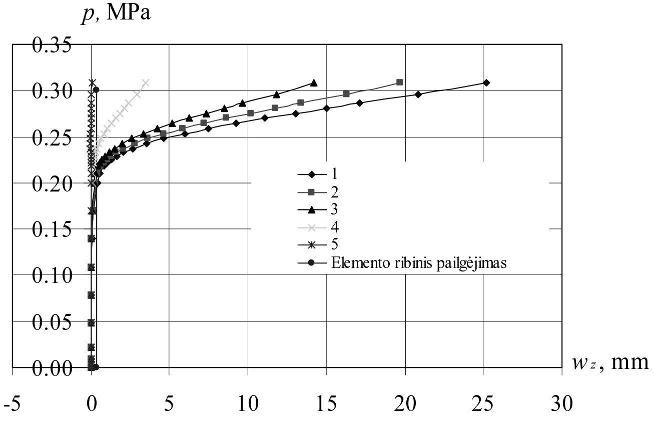


Fig 16. Curves of cross displacements of diaphragm nodes

The deformation behaviour of the diaphragm and the influence of various models may be exposed by comparing different curves representing pressure *p* and central deflection (Fig 17).

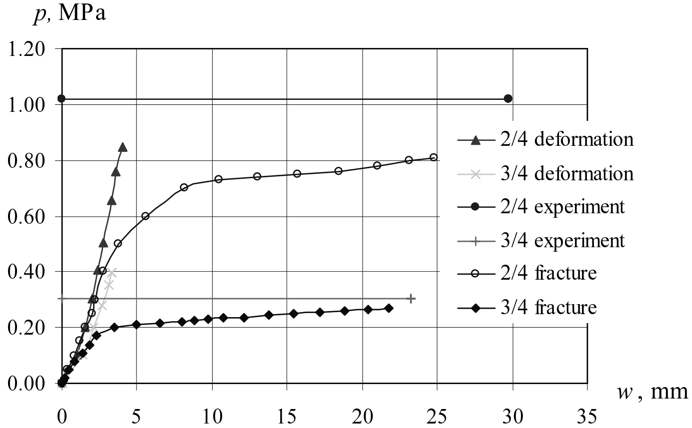


Fig 17. Displacement curves of various models of diaphragms

Increase of incision depth from 0.30 mm to 0.45 mm decreases the critical pressure of diaphragm by 0.50 MPa.

Generalizations and conclusions

Summarizing results of the research conducted with diaphragms of the shock tube, the following conclusions can be drawn:

1. Based on the data founded in the literature it could be stated that the potential of the numerical modelling as an advance investigation tool for predicting the deformation and fracture behaviour of the shock tube diaphragms is not fully employed. The available studies are restricted to brittle diaphragms and slender diaphragms without incisions. Investigation of the slender elastic – plastic diaphragms with uniform thickness and diaphragms with incisions, in particular, is still missing.
2. The developed computational 2D and 3D finite element models of the diaphragm without incisions were examined by comparing them with classical analytical solutions and experimental results. It has been found that numerical linear models perfectly fit explicit solution. In the case of nonlinear models, numerically and experimentally obtained central residual deflections of the considered diaphragms have 13 % difference.
3. 3D model of diaphragms with incisions was developed by parametric modification of 3D primary mesh in the vicinity of the incision. The quality of the model was tested and indirectly demonstrated by comparing the displacements of the diaphragms with 50 % incision depth with experimental

results. 23 % discrepancy appeared to be an adequate quality indicator for such a sensitive object.

4. Numerical investigation of the influence of incision depth on the load-carrying capacity, based on deformation criterion, revealed that the increase of incision depth by 25 %, 50 % and 75 % reduces load-carrying capacity by 1.67, 2.18 and 2.31 times, respectively.

5. According to deformation criterion, numerically evaluated critical pressure of the diaphragm with 50% incision depth is 0.84 MPa and yields 17 % difference compared to experimental results. Consequently, 75 % incision depth yields critical pressure of 0.398 MPa and 23 % difference compared to experimental results.

6. Experimentally determined critical pressure for the diaphragm with 50% defect depth is 31.3 % higher than the numerical value obtained according to fracture criterion. For diaphragms with 75 % incision depth, the critical pressure is, however, by 34.6 % higher. It means that numerical results presents the lower limit value of pressure.

7. The obtained numerical results proved that the suggested finite element model qualitative by describes the opening behaviour of the diaphragm. For diaphragms with 75 % incisions under proportional loading, the deflection of a particular “petal” gives 6.0 % differences, while for diaphragms with 50 % incisions it gives 22.1 %.

8. It was observed that spreading of the plastic strain zones provides information relating to the incision depth with the fracture pattern. In particular, deeper incisions reduce plastic concentration along the contour, thereby reducing a possibility of irregular fracture of the diaphragms in the vicinity of the contour.

9. Based on theoretical considerations and numerical and experimental results, it can be recommended for potential users of slender diaphragms with incisions to predict and take into account critical pressure values and possible opening mechanisms of the diaphragm.

List of Published Works on the Topic of the Dissertation
In the reviewed scientific periodical publications

1. TRETJAKOVAS, J.; KAČIANAUSKAS, R.; ŠIMKEVIČIUS, Č. Nonlinear FE Analysis of the Shock Tube Diaphragm Behavior under Pressure. *Mechanika*, Kaunas: Technologija, 2004, Nr. 6. (50), p. 24–29. ISSN 1392–1207. (INSPEC).
2. TRETJAKOVAS, J.; KAČIANAUSKAS, R.; ŠIMKEVIČIUS, Č. FE simulation of fracture of a diaphragm with initiated defect. *Mechanika*,

Kaunas: Technologija, 2006, Nr. 6 (62), p. 5–10. ISSN 1321–1207. (INSPEC).

In the other editions

3. TRETJAKOVAS, J. Modelling of nonlinear bending plates by FEM. In *Proceedings of the VI Conference of Lithuanian Young Scientists "Lithuania without science – Lithuania without future", held in Vilnius on 15-16 April, 2003, p. 90-96. Mathematics. Informatics* (6–oios Lietuvos jaunųjų mokslininkų konferencijos „Lietuva be mokslo – Lietuva be ateities", įvykusios 2003 m. balandžio 15–16 d. Vilniuje, medžiaga. Matematika. Informatika). Vilnius: Technika, 2003, p. 90–96 (in Lithuanian). ISBN 996-05 620-9.
4. TRETJAKOVAS, J.; KAČIANAUSKAS, R. Three-dimensional FE simulation of the behavior of thin membrane with initiated defect. In *Proceeding of the 8th conference "Shell structures: Theory and applications", Jurata, Poland, 12–14 October 2005.* London/Leiden/NewYork/Philadelphia/Singapore: Taylor & Francis, 2005, p. 507–510. ISBN 0 415 38390 0 (ISI Proceedings).

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DIAFRAGMOS SMŪGINIAME DUJŲ VAMZDYJE DEFORMAVIMO IR IRIMO MODELIAVIMAS

Mokslo problemos aktualumas. Smūginis dujų vamzdis yra vienas iš dažniausiai naudojamų įrenginių smūginėms bangoms gauti. Smūginiai vamzdžiai paprastai naudojami aerodinamikoje (skraidymo aparatų – raketų, lėktuvų ir kt. – modelių bandymuose), dujinėse patrankose, apsauginiuose vožtuvuose, metrologijoje (slėgio ir temperatūros jutiklių dinaminėms charakteristikoms identifikuoti). Paskutiniais dešimtmečiais jie sėkmingai buvo pritaikyti cheminėse technologijose (aukštų temperatūrų cheminės kinetikos studijoms, medžiagų sintezei ir materijos kondensavimui), medicinoje (klausos aparatams konstruoti) ir kitur.

Viena pagrindinių smūginio dujų vamzdžio sudedamųjų dalių yra diafragma, skirianti vamzdžio aukšto ir žemo slėgio kameras. Jai staigiai atsivėrus susidaro smūginė banga. Atsivėrimo proceso pobūdis, esant tampriam-plastiniam diafragmos irimui, yra vienas iš svarbiausių veiksnių, dėl kurių susidaro banga. Diafragmos irimo pobūdis priklauso nuo diafragmos medžiagos, matmenų, ypač nuo specialiai inicijuojamos įpjovos geometrinių parametrų, nuo naudojamų darbinių (aukšto slėgio kameroje) ir tiriamųjų (žemo slėgio kameroje) dujų, nuo įtvirtinimo vamzdyje ir kitų veiksnių.

Paskutiniais dešimtmečiais šis sudėtingas procesas buvo nagrinėjamas dažniausiai eksperimentiniais ir kiek rečiau skaitiniais metodais. Patikimas proceso modeliavimas skaitiniais metodais tapo įmanomas visai neseniai, kai atsirado didelio pajėgumo kompiuteriai ir tapo tobulesni skaičiavimo metodai.

Moksliškai pagrįstas diafragmos projektavimas ir eksploatavimas yra svarbus technologijų uždaviniai, o skaitinio modeliavimo rezultatai yra veiksnys, padedantis racionaliai spręsti šiuos uždavinius.

Darbo tikslas ir uždaviniai. Tikslas – skaitiniais metodais aprašyti ir ištirti liaunos diafragmos su įpjova deformavimosi ir irimo procesus, išnagrinėti įpjovos gylio įtaką šiems procesams ir pateikti rekomendacijas. Šiam tikslui pasiekti buvo iškelti tokie uždaviniai:

1. Eksperimentiškai ištirti diafragmų deformavimą ir irimą.
2. Skaitiniais metodais modeliuoti liaunų diafragmų su įpjovomis ir be jų deformavimosi elgseną ir irimą.
3. Ištirti įpjovos gylio įtaką diafragmos deformavimuisi ir irimui.

Mokslinis naujumas ir originalumas. Išnagrinėjus ir palyginus įvairius skaičiuojamuosius baigtinių elementų modelius buvo ištirta ir nustatyta įpjovos geometrijos įtaka smūginio dujų vamzdžio liaunos diafragmos su kryžmine įpjova kritiniam slėgiui pagal ribinius deformavimo ir irimo kriterijus.

Atlikti originalūs eksperimentiniai diafragmų deformavimo ir irimo tyrimai.

Tyrimų objektas ir metodai. Darbe tyrimo objektas yra smūginio dujų vamzdžio diafragma – apvali plona liauna plokštelė su kryžmine įpjova.

Baigtinių elementų metodu nagrinėjamas smūginio dujų vamzdžio diafragmos deformavimas ir irimas bei šių reiškinių priklausomybė nuo diafragmos įpjovų geometrijos. Remiantis eksperimentų rezultatais buvo siekiama įvertinti baigtinių elementų metodu gautus sprendinius.

Teorinė ir praktinė vertė. Taikant pasiūlytą trimatį diafragmos su įpjova baigtinių elementų modelį ištirti diafragmos atsivėrimui svarbūs rodikliai: kritinis slėgis, deformavimosi elgsena, plastinių zonų kaupimosi vietos ir aprašytas irimo procesas.

Remiantis gautais rezultatais pateiktos rekomendacijos apie liaunos diafragmos kryžminės įpjovos matmenis. Gauti rezultatai yra svarbūs planuojant eksperimentus smūginiame vamzdyje.

Darbo apimtis. Darbą sudaro bendra darbo charakteristika, 5 skyriai, išvados, literatūros sąrašas (106 pozicijos) ir publikacijų sąrašas. Bendra disertacijos apimtis – 88 puslapiai, 69 iliustracijos ir 4 lentelės.

Darbo turinys

Įvadiniame skyriuje apibrėžta tyrimų sritis ir aktualumas, aprašyta mokslo krypties problema, suformuluotas darbo tikslas ir iškeltieji uždaviniai, paminėti naudotieji tyrimo metodai, aptartas darbo naujumas ir originalumas, paaiškinta praktinė vertė, pateikta aprobacija.

Pirmajame skyriuje aprašytas smūginis dujų vamzdis, jo panaudojimo galimybės ir konstrukcija koncentruojant dėmesį į vamzdžio diafragmą, jos tipus, elgseną ir irimą, pateikiama tyrimų apžvalga.

Antrajame skyriuje pateiktas diafragmos skaičiuojamasis modelis sudarytas baigtinių elementų metodu, aprašyti dvimačio ir trimačio modelio sudarymo etapai, pateikti testavimo rezultatai.

Trečiajame skyriuje aprašyti atlikti originalūs smūginio dujų vamzdžio diafragmų deformavimo ir irimo eksperimentiniai tyrimai.

Ketvirtajame nagrinėjamas diafragmų be ir su inicijuotomis įpjovomis netiesinis deformavimas baigtinių elementų metodo pagalba. Buvo tirta kryžminės įpjovos geometrijos įtaka.

Penktajame skyriuje modeliuojamas ir analizuojamas diafragmos irimo procesas.

Disertacinio darbo pabaigoje pateiktas *literatūros* sąrašas.

Apibendrinimai ir išvados

Apibūdinus šiame darbe atliktus smūginio dujų vamzdžio diafragmos tyrimų rezultatus pateikiamos tokios išvados.

1. Literatūros analizė parodė, kad skaitinio modeliavimo kaip modernaus tyrimo instrumento galimybės, tiriant smūginių dujų vamzdžių diafragmų

deformavimą ir irimą, yra nepakankamai panaudotos. Žinomi darbai apsiriboja trapių diafragmų arba liaunų diafragmų be įpjovų tyrimais. Tačiau liaunų diafragmų (o tuo labiau konkretaus smūginio vamzdžio) su inicijuotomis įpjovomis elgsena skaitiniais metodais nėra tirta.

2. Palyginus modeliavimo tikslams sudaryto vientiso diafragmos baigtinių elementų modelio sprendinius su žinomais klasikiniais sprendiniais ir eksperimentų rezultatais nustatyta, kad sukurtas skaičiuojamasis modelis tiesinio uždavinio atveju idealiai atitinka žinomą analitinį sprendinį. Netiesinio uždavinio atveju apskaičiuoti liekamieji poslinkiai 13 % skiriasi nuo eksperimentinių tyrimo metu gautų rezultatų.

3. Diafragmai su įpjova modeliuoti pradinis vientisos diafragmos modelis buvo modifikuotas taikant sutankintą parametrinį tinklą įpjovos aplinkoje. Naujai sudaryto modelio kokybė patvirtinta lyginat diafragmos su 50 % įpjovos gyliu maksimalius liekamuosius centrinio taško skaitinius ir eksperimentinius poslinkius esant vienodam slėgiui. Nustatyta, kad gautas 23 % skirtumas yra priimtinas tokio jautrumo objektui.

4. Ištyrus skaitiniais metodais diafragmos su įvairiu įpjovos gyliu laikomąją galią prieširiminėje stadijoje pagal ribinių plastinių deformacijų kriterijų buvo nustatyta, kad didinant įpjovos gylį 25 %, 50 % ir 75 % diafragmos laikomoji galia lyginant su diafragma be įpjovos sumažėja 1,67, 2,18 ir 2,31 karto.

5. Apskaičiuotas kritinis slėgis pagal plastinių deformacijų kriterijų diafragmai su 50 % įpjovos gyliu lygus 0,84 MPa ir 17,7 % skiriasi nuo gauto eksperimentiškai, o diafragmai su 75 % įpjovos gyliu apskaičiuotas 0,398 MPa kritinis slėgis skiriasi nuo eksperimento metu gautų rezultatų 23 %.

6. Eksperimentiškai nustatytas kritinis slėgis diafragmai su 50 % įpjovos gyliu yra 31,3 % didesnis už jo reikšmę, apskaičiuotą pagal irimo kriterijų, o diafragmai su 75 % gylio įpjova – didesnis 34,6 %. Tai reiškia, kad skaitinis rezultatas nustato apatinę slėgio ribą.

7. Nustatyta, kad baigtinių elementu metodu apskaičiuotas irstančios diafragmos deformavimo pobūdis sutampa su eksperimento rezultatais, nes apskaičiuoti liekamieji centrinio taško įlinkiai diafragmai su 75 % įpjovos gyliu nuo eksperimentinio rezultato skiriasi 6,0 %, o diafragmai su 50 % įpjovos gyliu skirtumas siekia 22,1 %.

8. Skaitinių tyrimu metu nustatyta, kad pagal plastinių deformacijų laukų zonas galima spręsti apie įpjovų gylio įtaką irimo pobūdžiui. Didesnės įpjovos gylis sumažina plastinių zonų koncentraciją ties kontūru, taip sumažindamas diafragmos netaisyklingo plyšimo ties kontūru galimybę.

9. Remiantis atliktų teorinių, eksperimentinių ir skaitinių tyrimų rezultatais, siūloma smūginių dujų vamzdžių naudotojams pagal įpjovos

matmenis prognozuoti eksperimentą gautu skaitinio diafragmos su įpjova modelio sprendiniu, nustatyti ir žinoti diafragmų kritinius slėgius ir irimo pobūdį, kuris priklauso nuo plastinių deformacijų koncentracijos zonų.

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