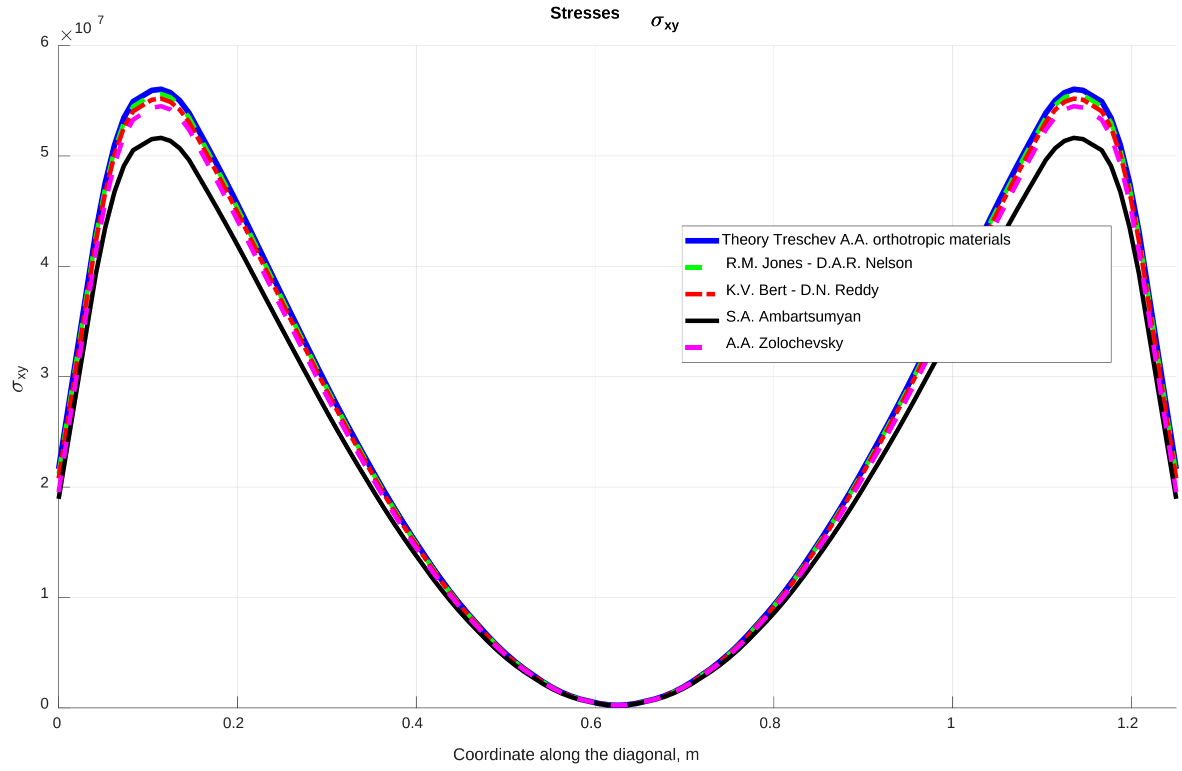

Fig. 25. Distribution of shear stresses σ_{xy} along the diagonal of platinum in the upper section

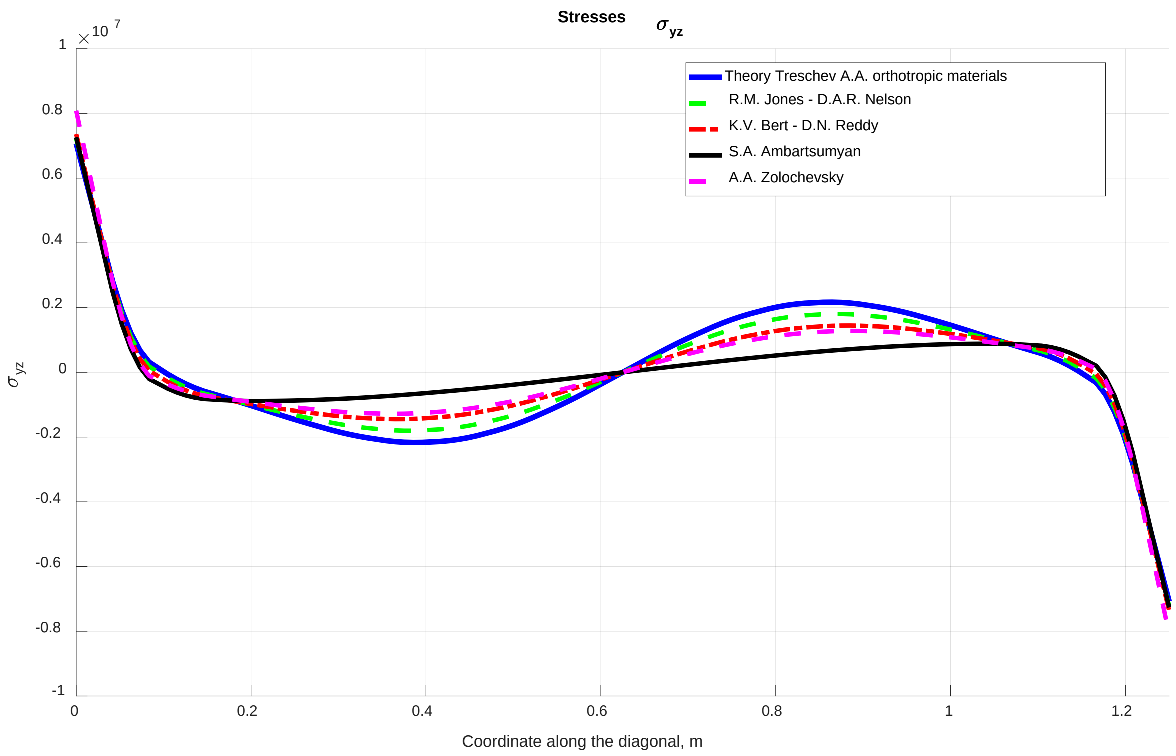

Fig. 26. Distribution of shear stresses σ_{yz} along the diagonal of the slab in the upper section

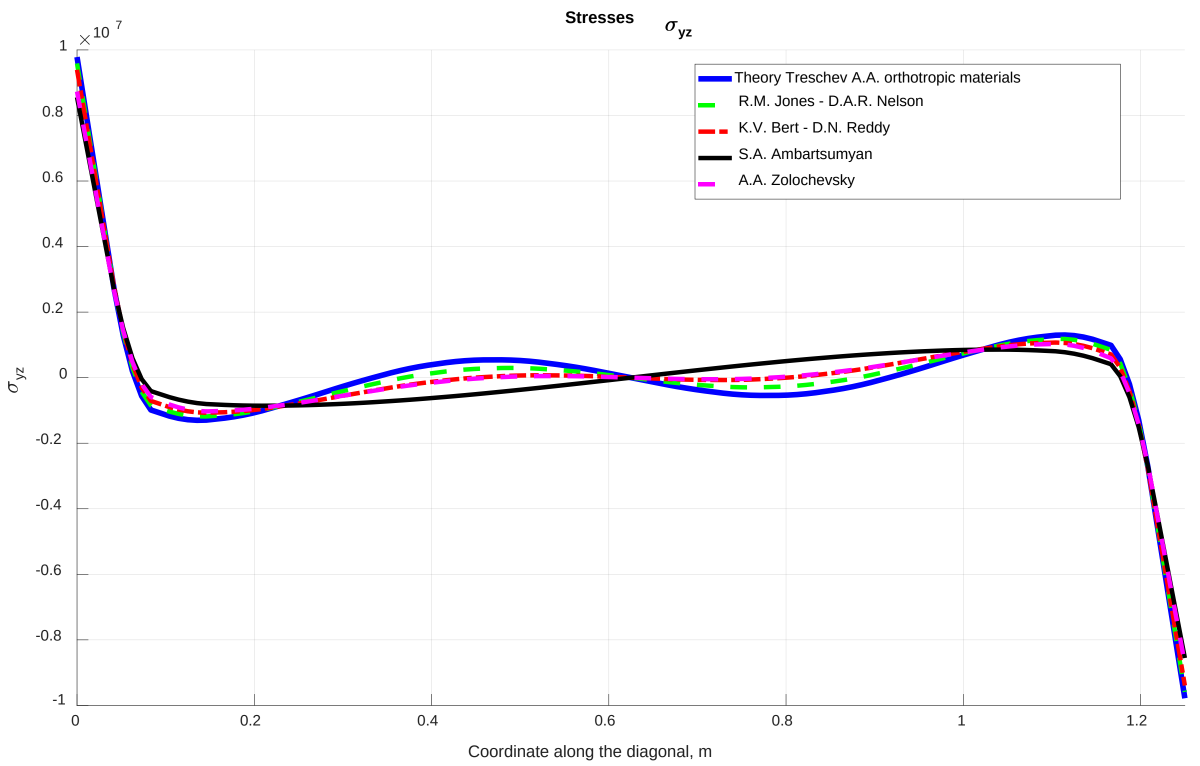

Fig. 27. Distribution of shear stresses σ_{yz} along the diagonal of the slab in the upper section

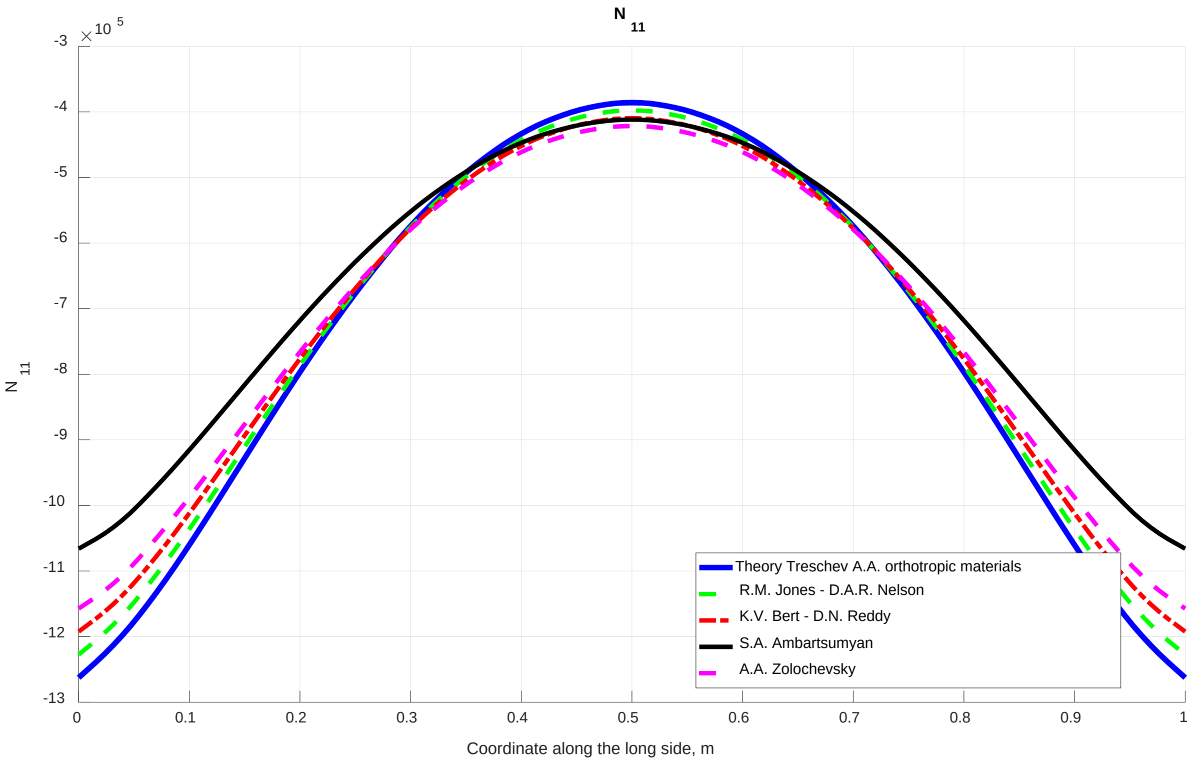

Fig. 28. Efforts N_{11} along the X_1 axis

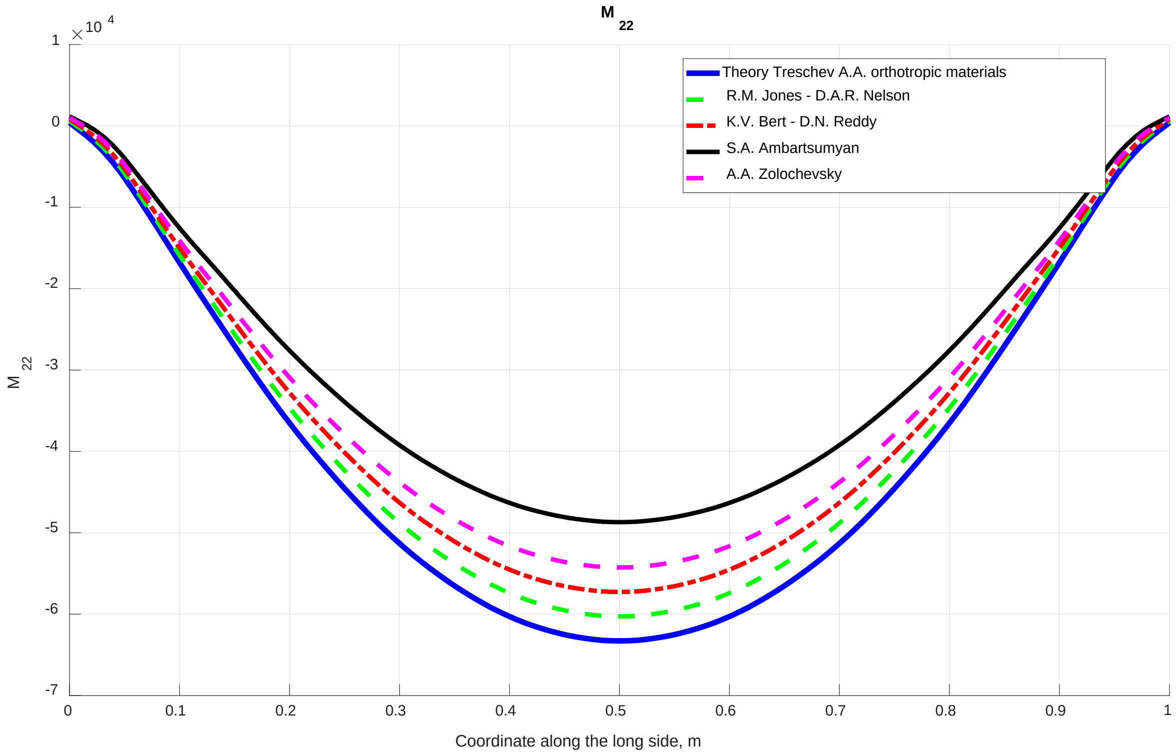

Fig. 29. Bending moment M_{22} along the X_1 axis

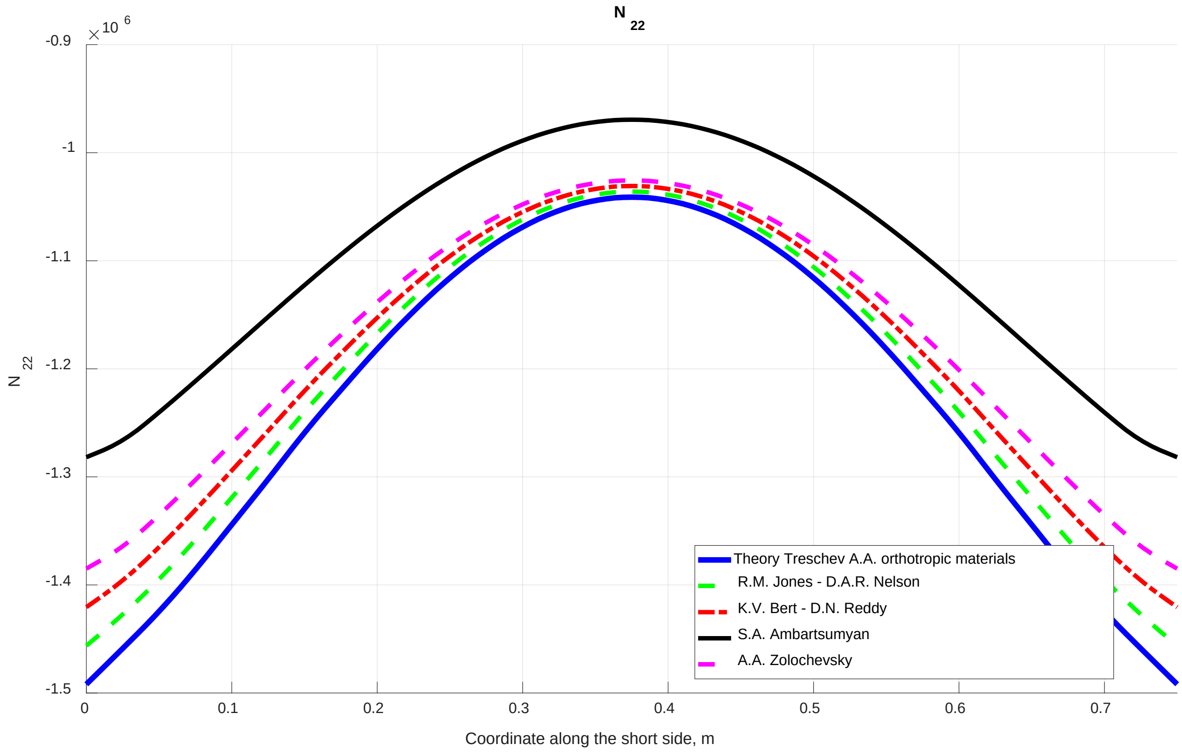

Fig. 30. Efforts N_{22} along the X_2 axis

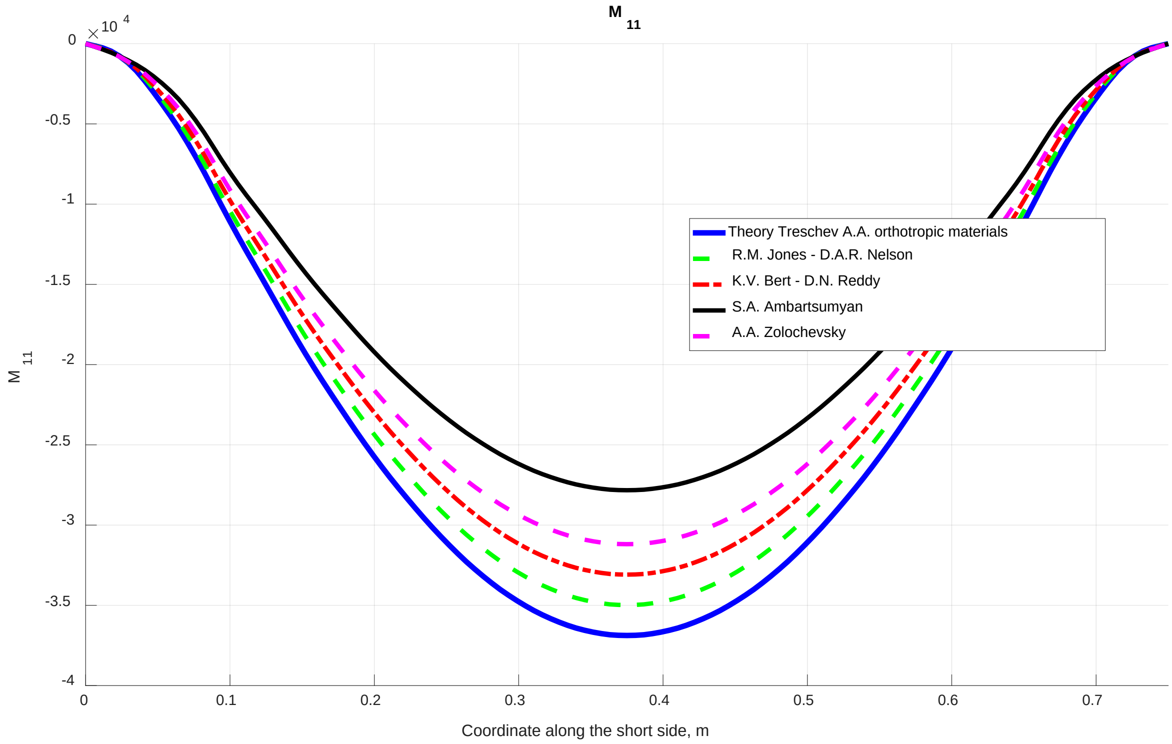

Fig. 31. Bending moment M_{11} along the X_2 axis

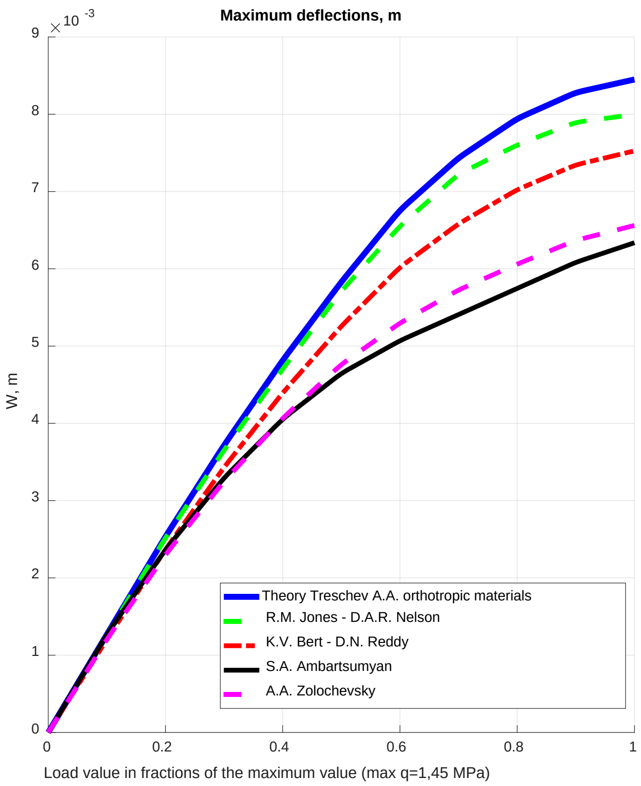

Fig. 32. Effect of load value on deflections

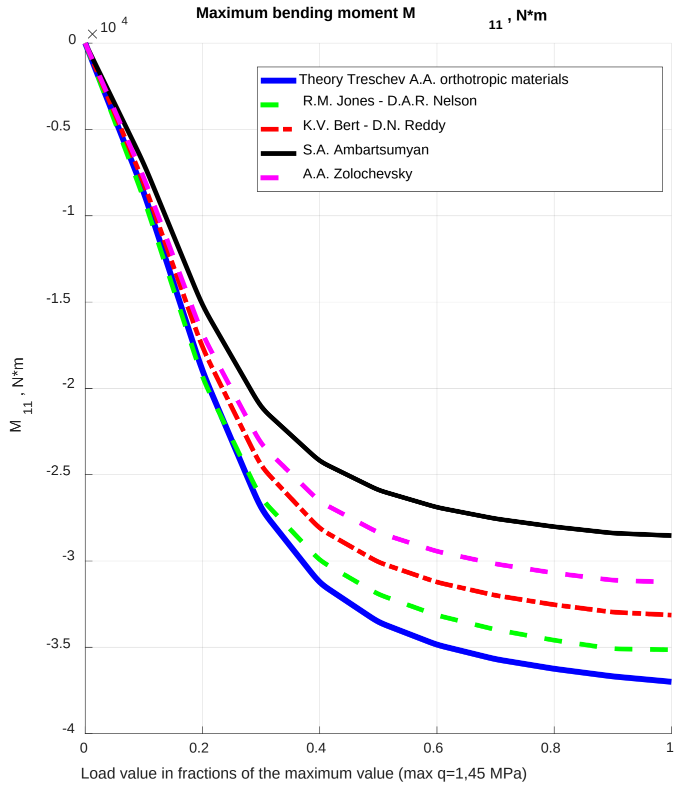

Fig. 33. Influence of the magnitude of the load on the maximum bending moment M_{11}

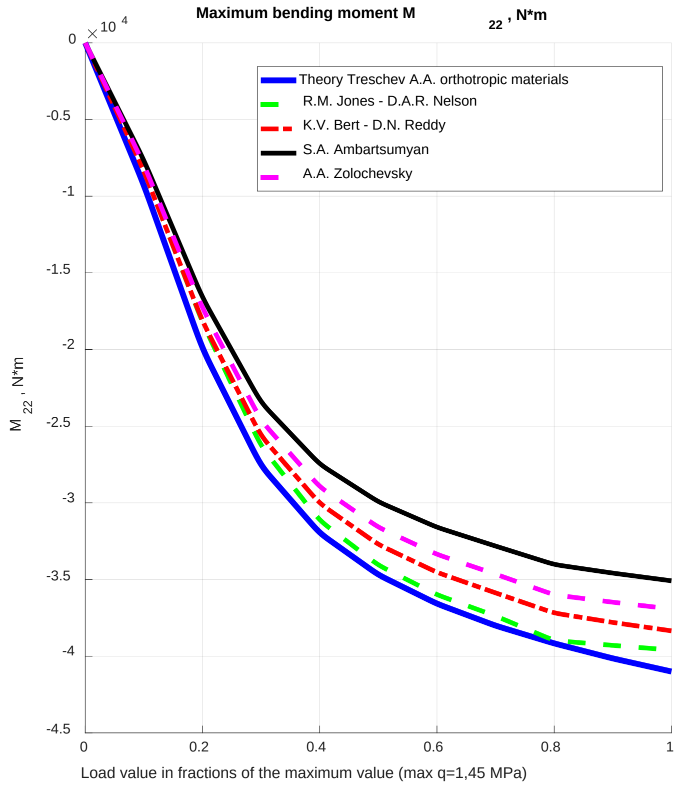

Fig. 34. Influence of the magnitude of the load on the maximum bending moment M_{22}

4. Summary

Analyzing the above graphical dependencies, it should be noted that the disregard for nonlinearity leads to a very significant error in the results. It should be said that when using materials in which the nonlinearity is more pronounced than that of the carbon fiber – carbon AVCO Mod 3a composite, and considering structures in large displacements and in a more complex stress-strain state, the stress-strain state will change even more significantly.

Based on the above, it can be concluded that this work is relevant and will serve as the first step towards a more accurate calculation of building structures within the framework of the proposed theory [32].

In a similar vein, the problem of axisymmetric transverse bending of an annular plate made of an orthotropic nonlinear material with different resistance was considered in [36]. During the deformation of the plate under consideration, there are no tangential stresses in the middle plane σ_{xy} and in the cross-section along the second coordinate σ_{yz}, and only tangential stresses in the cross-section along the radial coordinate σ_{rz} are taken into account. The presence of tangential stresses σ_{xy} and σ_{yz} (Figs. 5-8 and Figs. 24-27) significantly complicate the picture of the stress-strain state of rectangular plates due to the redistribution of stresses. Taking these stresses into account gives a more complete picture of the process of plate deformation during transverse bending, expanding the understanding of the picture of the stress-strain state of bent plates (especially the moment of the onset of the limiting state).

5. Conclusions

The main results and conclusions of the work are as follows:

1. A number of theories of deformation of nonlinear anisotropic materials with different resistances are considered, it is concluded that the constitutive relations used by the authors describe the process of deformation of plates made of these materials most fully.
2. The governing equations for the bending of rectangular plates of average thickness made of an orthotropic physically nonlinear material sensitive to the type of stress state are obtained in a geometrically linear formulation.
3. For a comparative analysis of the calculations of the proposed variant of deformation, the calculation of a rectangular plate of average thickness was carried out. The analysis of the results is demonstrated by the example of a rectangular plate with characteristic dimensions of 1.0×0.5×0.075 (a×b×h) m.
4. An algorithm for solving the resulting resolving equations based on the method of variable parameters of elasticity and finite-difference approximation of the second order of accuracy has been developed. Developed special software which implements the algorithm using MATLAB computing system to calculate the stress-strain state of the plates.
5. The results of the calculation of the plates showed that taking into account the phenomenon of nonlinear differential resistance allows obtaining more precise results, in comparison with the "linear theory of elasticity" and theories: S.A. Ambartsumyan, A.A. Zolochevsky, R.M. Jones – D.A.R. Nelson, C.W. Bert – J.N. Reddy up to 26.8% for maximum displacements, up to 38% for maximum stresses, and in some cases the difference for force factors can reach 60%;
6. The analysis of the results obtained allows us to conclude that it is necessary to take into account the phenomenon of nonlinear resistance of the material when carrying out strength calculations, due to the fact that this phenomenon has a significant effect on the qualitative and quantitative characteristics of the stress-strain state of structures (in particular, for a rectangular plate of average thickness).

Acknowledgements. *No external funding was received for this study.*

References

[1] Ambartsumyan SA. *Theory of anisotropic plates: strength, stability, vibrations*. Moscow: Nauka; 1967. (In Russian)
[2] Ambartsumyan SA. Basic equations and ratios of the multi-modular theory of elasticity of an anisotropic body. *Izv. Academy of Sciences of the USSR. MTT*. 1969;3: 51-61.
[3] Ambartsumyan SA. *Multi-modular theory of elasticity*. Moscow: Nauka; 1982. (In Russian)
[4] Ambartsumyan SA, Khachatryan AA. The basic equations of the theory of elasticity for materials of different resistance to tension and compression. *Inzh. journals MTT*. 1966;2: 44-53.
[5] Ambartsumyan SA, Khachatryan AA. Towards a multimodular theory of elasticity. *Ing. journals MTT*. 1966;6: 64-67.
[6] Jones RM. A Nonsystemmetric Compliance Matrix Approach to Nonlinear Multimoduls Ortotropic Materials. *AIAA Journa*. 1977;15(10): 1436-1443.
[7] Jones RM, Nelson DAR. Material for nonlinear Deformation. *AIAA Journal*. 1976;14(6): 709-716.
[8] Jones RM. Modeling Nonlinear Deformation of the Carbon-Carbon Composite Materials. *AIAA Journal*. 1980;18(8): 995-1001.
[9] Jones RM. Stress-Strain Relations for Materials with Moduli in Tension and Compression. *AIAA Journal*. 1977;15(1): 16-25.
[10] Bert CW. Models for fibrous composities with different properties in tension and compression. *J. Eng. Matls. and Tech., Trans. ASME*. 1977;99HD(4): 344-349.
[11] Bert CW. Micromechanics of the different elastic behavior of filamentary composites in tension and compression. In: Bert CW. (ed.) *Mechanics of Bimodulus Materials.* 1979. p.17-28.
[12] Bert CW. Gordaninejad F. Multi-modular Materials. *International Journal for Numerical Methods in Engineering*. 1984;20: 479-503.
[13] Bert CW, Reddy JN, Chao WC. Bending of Thick Rectanqular Plates Laminated of Bimodulus Composite Materials. *AIAA Journal*. 1981;19(10): 1342-1349.
[14] Zolochevsky AA. To tensor coupling in the theories of elasticity and plasticity of anisotropic composite materials that are differently opposed to tension and compression. *Mechanics of Composite Materials*. 1985;1: 53-58.
[15] Zolochevsky AA. Determining equations and some problems of the multimodular theory of elasticity of anisotropic materials. *PMTF*. 1985;4: 131-138.
[16] Zolochevsky A.A. On the theory of plasticity of materials differently resisting tension and compression. *Izv. universities. Engineering*; 1986;6: 13-16.
[17] Zolochevsky AA. On the relations of the theory of elasticity of anisotropic multi-modular materials. *Dynamics and durability of machines*. 1981;34: 3-8.
[18] Zolochevsky AA. Ratios of the multimodular theory of elasticity of anisotropic materials based on three mixed invariants. *Dynamics and Strength of Machines*. 1987;46: 85-89.
[19] Zolochevsky AA, Morachkovsky OK. The directions of development of models and methods for calculating the nonlinear deformation of bodies and elements of engineering structures. *Dynamics and strength of machines*. 1989;50: 3-9.
[20] Zolochevsky AA, Sklepus SN. On the theory of plasticity with three invariants of the stress state. *Izv. universities. Engineering.* 1987;5: 7-10.
[21] Zolochevsky AA. Concerning consideration of the multiresistance in the theory of creep of isotropic and anisotropic materials. *PMTF*. 1982;4: 140-144.
[22] Lomakin EV. Multi-modularity of composite materials. *Mechanics of composite materials*. 1981;1: 23-29.

[23] Lomakin EV. Relations of the theory of elasticity for an anisotropic body, the deformation characteristics of which depend on the type of stress state. *Izv. Academy of Sciences of the USSR. MTT*. 1983;3: 63-69.
[24] Berezin IS, Zhidkov NP. *Computing methods vol. 1*. Moscow: State publishing house physical. lit-ry; 1959. (In Russian)
[25] Treschev AA. *The theory of deformation and strength of materials sensitive to the type of stress state. Defining relations*. Moscow: RAASN; 2008. (In Russian)
[26] Matchenko NM, Treschev AA. *Theory of deformation of materials with different resistance. Determining relations.* Tula: TSU; 2000. (In Russian)
[27] Treschev AA. To bending of thick rectangular orthotropic slabs made of nonlinear materials sensitive to the type of stress state. In: *Proceedings of the 7th International Conference «Actual Problems of Construction and Building Industry»*. Tula: TulSU; 2006. (In Russian)
[28] Treschev AA. *The theory of deformation and strength of materials with initial and induced sensitivity to the type of stress state. Defining relations: monograph*. Moscow: RAASN; 2016. (In Russian)
[29] Treschev AA. Description of deformation of nonlinear anisotropic materials. *Architectural and construction materials science at the turn of the century: materials of reports of the International conference*. Belgorod: BelGTASM; 2002. (In Russian)
[30] Treschev AA. Description of nonlinear deformation of anisotropic materials *Problems and achievements of construction materials science*. Belgorod: BSTU; 2005. p. 233-234. (In Russian)
[31] Treschev AA. *Anisotropic plates and shells of materials with different resistance: monograph*. Moscow: RAACS; 2007. (In Russian)
[32] Treschev AA, Romashin DA. Defining relations for nonlinear anisotropic materials sensitive to the type of stress state. *Bulletin of Nizhny Novgorod University. N.I. Lobachevsky*. 2011;4(4): 1740-1742.
[33] Birger IA, Mavlyutov RR. *Resistance materials: Tutorial.* Moscow: Science. Ch. ed. Phys. Mat. lit.; 1986. (In Russian)
[34] Pisarenko GS, Mozharovsky NS. *Equations and boundary value problems of the theory of plasticity and creep. Reference book.* Kiev: Science; 1981. (In Russian)
[35] Jones RM, Nelson DAR. Theoretical-experimental correlation of material models for nonlinear deformation of graphite. *AIAA Journal*. 1976;14(10): 1427-1435.
[36] Zhurin EA, Treschev AA. Bending of ring plates, performed from an orthotropic nonlinear differently resistant material. *International Journal for Computational Civil and Structural Engineering*. 2020;16(1): 130-146.