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Ultimate capacity of ship hull structures in the works of Prof. Marian Kmiecik

SUMMARY

A monographic review of the most important results of Prof.Kmiecik's scientific works on the ultimate strength (load carrying capacity) of ship structures is presented in the paper. The works have been classified into the following five groups:

- *experimental research on the ultimate capacity*
- *research on the identification of real structure properties*
- *analytical and numerical research on the ultimate capacity*
- *research on the probabilistic approach to the ultimate capacity.*

The fifth topic group : a short synthesis of the scientific outcome of Prof.Kmiecik concerning the areas is given at the end of the paper.

The paper presented at the Symposium on Ship Structure and Mechanics: Ultimate Capacity of Ship Structures, held in memoriam of Prof. Marian Kmiecik, 20 and 21 March 1996, Szczecin.

AUTHOR'S NOTE

The paper is the first attempt to systematically present Prof. Kmiecik's works on the ultimate capacity of ship structures. This was the research area (among others not reviewed here) which Prof. Kmiecik devoted most of his time to and his whole academic and scientific career was based on. It was impossible to avoid many shortenings and generalizations which appeared in result of the scheme imposed on the article. The author apologizes for any shortcoming of his work and kindly expects comments from the Readers.

INTRODUCTION

Prof.Kmiecik revealed his interest in the ultimate capacity of structures as early as at the end of the 1950s. His first publication on the theme appeared in 1959 [1]. For the next several years he carried out further studies and works in the direction, preparing himself to undertake a scientific research position in Trondheim, Norway. From that moment till the last months of his life Prof.Kmiecik consequently developed research works in the area. Tens of his papers and lectures on the ultimate capacity problems were published. He was the co-author of three scientific books [33,48,50], author or co-author of many research reports, he served several times as the professor conferring the D.Sc. degree or the D.Sc. thesis reviewer in the area in question. The list of his publications contains first of all the works of the fundamental character. But Prof.Kmiecik's scientific outcome has been supplemented by the applied research works, not less important, but making scientific research results closer to the industrial practice, the domain which Prof.Kmiecik was involved in for all the time of his professional career. In his bibliography many publications can be found resulted from his worldwide activity within the International Ship Structures Congress [12,25,34,43,49], ship classification societies, e.g [28], and due to participation in many international scientific conferences, seminars and lectures.

Prof.Kmiecik was not only an individual researcher but also inspirator of team work who was able to instill his own research passion to the team. He allowed to develop further his ideas by collaborators and even expected this from them. It can be confirmed by many collective publications where Prof.Kmiecik appears as the co-author. Many works published by large group of his disciples and many quotations of his works additionally witness his life achievements.

All his scientific outcome in the area of the ultimate capacity of ship structures can be split into the following topic groups and time periods (phases):

- experimental research on the ultimate capacity of structures, the 1960s and 1970s
- identification of the real ship structure properties, the 1970s and 1980s
- analytical and numerical research on the ultimate capacity, the 1970s and 1980s
- research on the probabilistic approach to the ultimate capacity of structures, the 1990s
- synthesis of the research results in question, the 1980s and 1990s.

The division is obviously conventional because Prof. Kmiecik interspersed different lines of his scientific activity and often made use of his earlier scientific results in later investigations.

EXPERIMENTAL RESEARCH ON THE ULTIMATE CAPACITY OF STRUCTURES

The idea of carrying experiments on ship structure ultimate capacity appeared in the Prof.Kmiecik's scientific plans probably in the middle of the 1960s. He, then an engineer at the beginning of his professional and scientific career, undertook such experiments to evidence correctness of the thesis that there is a difference between the influence of imperfections on the load carrying capacity of the bar-beam structures and that of typical ship plate structures. The fundamental work for all scientific activity of Prof.Kmiecik was the report titled: „*The Load-Carrying Capacity of Axially Loaded Longitudinally Stiffened Plate Panels Having Initial Deformations*" published in 1970 [2]. The report summarized results of the experiments carried out for more than two years during his scientific stay in the Ship Research Institute of Norway, Trondheim. The 1m x 2m steel panel models built of plates and stiffeners and having the geometrical proportions typical of ship structures, shown in Fig.1, were investigated in accordance with the Prof. Kmiecik's original research program. The work provided many conclusions concerning the behaviour of the stiffened plate structures under compressive load up to panel buckling and loss of load carrying capacity. The most important conclusion of the experiments was the following:

„*Initial distortions of plates can detrimentally influence their strength only then if at least one shape component of the distortions is similar to the shape of the elastic deflections which appear only after the loss of stability of the ideally flat plates. If the condition is not fulfilled, the initial distortions of plates can be advantageous*".

The theoretical investigations contained in the next work [4] supplemented the experiment research report. The results of the work were widely commented in the scientific circles and quoted by different authors all over the world. It also became the background of receiving the degree of Doctor of Technical Sciences by him in the Technical University of Gdańsk in 1971 [3]. Two further research directions emerged from the work to be undertaken by Prof.Kmiecik and his team:

- numerical investigations with the use of the finite element method, and
- statistical investigations aiming at the properties identification of the real ship structures, first of all, the ship plate postwelding distortions.

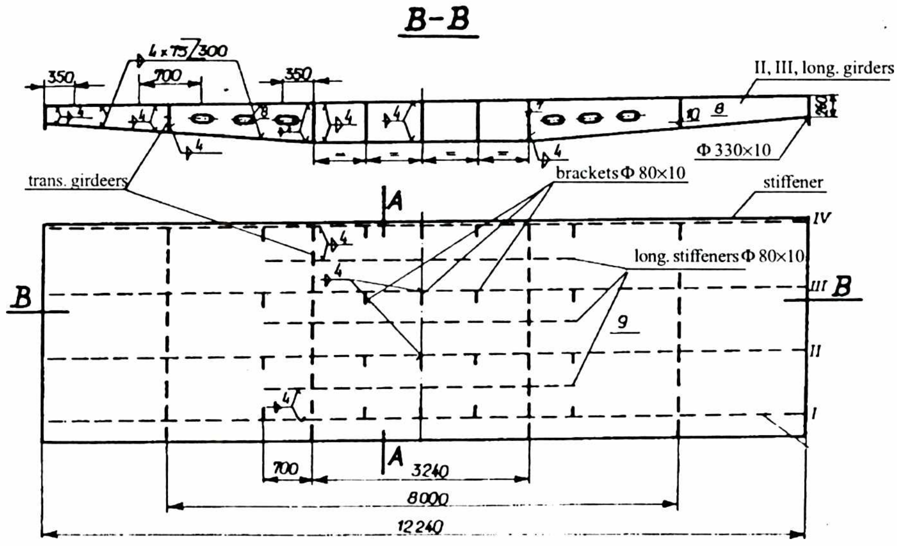


Fig.2. Structural scheme of the hatch cover tested in Warszawa, 1976 [7,11]

The idea which permanently absorbed Prof.Kmiecik was to put results of the research on load carrying capacity into practice, viz. the application of the ultimate load method to ship structure design, the first attempt of which was his early publication of 1959 [1]. The next experimental research inspired by him was that on load carrying capacity of ship hatch covers. In 1976 three full-scale hatch covers designed for a ship to be built by the Szczecin Shipyard, were tested (Fig.2). The experiments were performed in the Building Technology Laboratory, Warszawa, under Prof.Kmiecik's supervision and with the assistance of the Polish Register of Shipping. From the experiments it resulted that the load carrying capacity of plate panels, governed by their slenderness, is decisive for the capacity of the entire hatch cover [7,11].

Prof.Kmiecik planned to carryout extensive experiments on the ultimate capacity of structures.To put the plans into effect he initiated the design and construction of the strength laboratory of ship structures in the Ship Research Institute, Technical University of Szczecin, according to his original concept and under his supervision. However the realities of life and lack of money allowed only to complete the laboratory hall, assemble the stand foundation and collect some part of the measurement equipment.

Nevertheless his ideas and scientific inspiration yielded a crop in other laboratory centres (e.g. of the technical universities in Gdańsk and Delft) where his collaborators and disciples carried out research works. Prof.Kmiecik intended to carry out research experiments till the last years of his life which could be confirmed by the next, elaborated by him in 1989, predesign of the laboratory research on the ultimate capacity of stiffened plate models, to obtain tools for verifying the results of numerical investigations and simplifying evaluations of the ultimate capacity of structures [37].

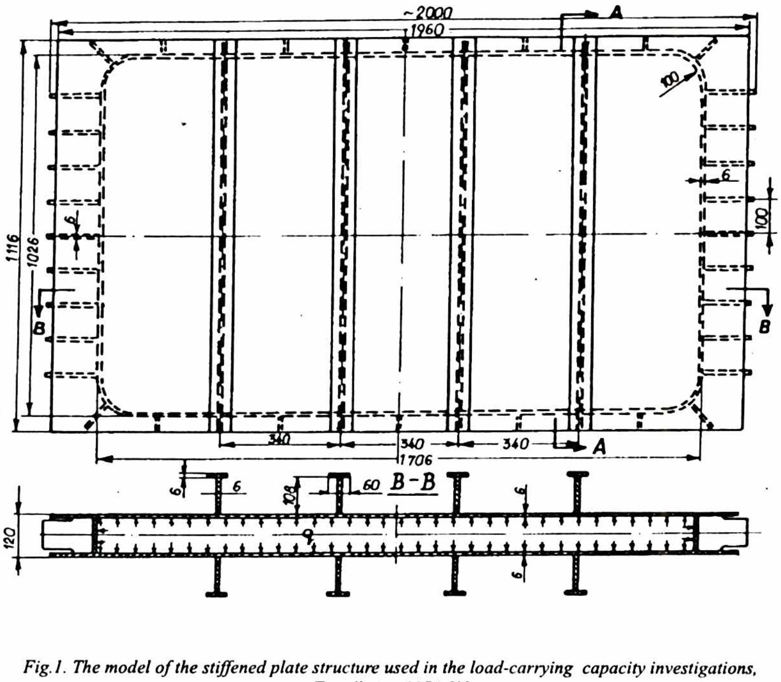


Fig.1. The model of the stiffened plate structure used in the load-carrying capacity investigations, Trondheim, 1970 [2]

IDENTIFICATION OF REAL STRUCTURE PROPERTIES

The conclusion from the experimental research concerning the influence of the initial distortions of plates on the load carrying capacity of structures, supported by the theoretical considerations presented in e.g. [5] was a motive for undertaking by Prof.Kmiecik and his team extensive investigations on the imperfections of real structures. The main tide of the investigations carried out since the middle of the 1970s [6] was the measurements and statistical analyses of fabrication distortions of the plating of different ship structures. The investigations were continued in some Polish shipyards and one German shipyard till the middle of the 1980s. In some of the works, apart from measurements, attempts can be found to analytical determination of the imperfections, mainly postwelding residual stresses, see e.g. [14].

The plate deflection measurements were performed on more than 2000 plate panels. A special data bank was established to analyze the measurement results, which enabled to approximate deflection shape by means of the double Fourier series, and then to carry out statistical analyses, distribution approximations, regression and correlation calculations. Results of the works are contained in several internal reports and publications e.g. [23,24,28,30,45]. A synthesis of the works on ship plates appeared in the „ Marine Structures" journal in 1995 [52], already after the death of Prof. Kmiecik. The results provided the complete data on the real plate shapes and their components, as well as the relationships between the maximum values of the deflections and deflection components and plate geometrical parameters (see e.g. Fig.3 and 4).

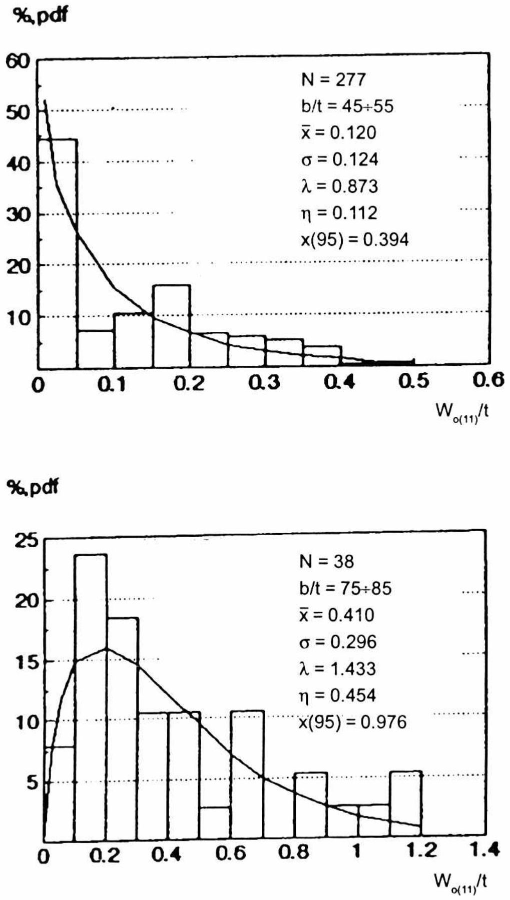


Fig.3. The sample histograms and Weibull's distribution approximations of some plate deflection components [52]

The investigation results on the ship plate deflection identification together with the theoretical and numerical calculations of the load carrying capacity of structures were used by Prof.Kmiecik as the basis of a separate applied research aimed at the formulation of rational backgrounds for the standards of the allowable distortions of ship hull structures.

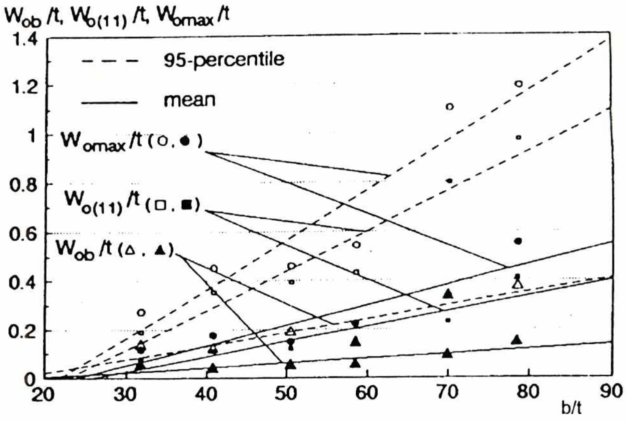


Fig.4. Regresion results of plate deflection values

Prof.Kmiecik presented his opinion on the theme to demonstrate first of all that the plate deflection tolerances should be established on the basis of the statistical considerations and rational strength criteria [14,20]. From the 1970s he consequently demonstrated that the common opinion about the detrimental effects of plate imperfections must be reconsidered because any decision to straighten a plate panel can be rationally justified only when its shape is known in detail. If this approach is accepted it will be possible to reduce extent of the expensive straightening operations of structures [8]. One of the meaningful publications in the respect was the article, based on his lecture given at Lloyd's Register, London, in 1986 [28].

Prof.Kmiecik intended to construct a device for quick shape control of plating and implement it into daily shipyard routine; unfortunately he did not manage to do it.

The publication [36], which Fig.5 is taken from, summarizes his research works on the ship plate distortions and provides the tolerance proposals for them.

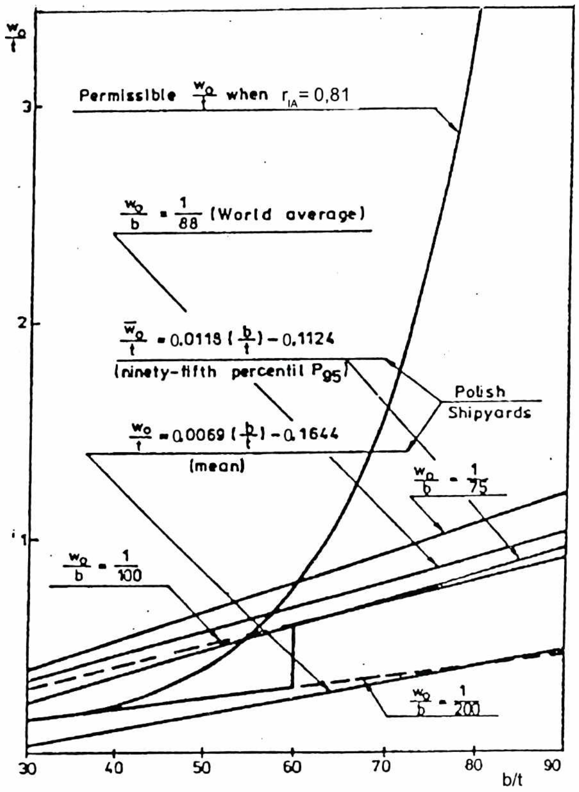


Fig.5. New tolerance proposals for the plate distortions versus different standard tolerances

ANALYTICAL AND NUMERICAL RESEARCH ON THE ULTIMATE CAPACITY OF STRUCTURES

The experimental research performed in Trondheim was used by Prof.Kmiecik as a starting point to and a verification basis of the theoretical considerations contained in the next report titled: „*Behaviour of Axially Loaded Simply Supported Long Rectangular Plates Having Initial Deformations*" issued in 1971 [4]. In the report the theoretical solution of highly nonlinear behaviour of such plates, including the „*snap-back*" effect are of special value. The geometrical proportions of the theoretical models corresponded to those of the earlier tested physical ones. To solve the problem of the plates with large deflections (of the plate thickness order) Prof.Kmiecik applied the known von Karman - Marguerre equations and solved them with the use of the Ritz energy method. He proved, by using results of the calculations carried out for plates with different forms of initial deformations, the earlier stated hypothesis that the behaviour of plates is influenced by the initial deformations with strong dependence on their form and geometrical proportions of the plates. The results are exemplified in Fig.6.

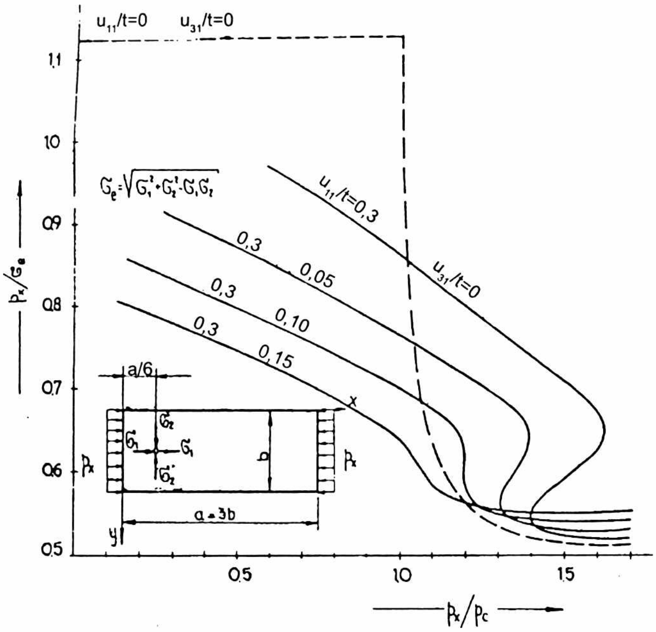


Fig.6. The maximum values of the reduced stress in the plate having initial deformations versus axial load applied to it [4]

Algorithms and numerical calculation programs

The important area of Prof.Kmiecik's activity was the elaboration of the numerical calculation programs based on the finite element method (FEM), aimed at the nonlinear analysis of ship imperfect plate behaviour. The incremental equations of the nonlinear theory of plates with initial (residual) stresses and distortions, formulated for the elastic-plastic strain range of material and with the use of the FEM, described e.g. in [17,19], were the basis for Prof.Kmiecik and his team to develop the algorithm and calculation programs of the load carrying capacity of plates at the beginning of the 1980s [22,27]. The software system installed at first on an ICL computer was then modified and updated to operate on PCs. Fig.7 presents the set of programs which form the system called PANFEM. The system was installed in several foreign research centres (in Denmark, the Netherlands, Germany, Portugal) which Prof.Kmiecik and his team cooperated with, as well as in Poland in the Ship Design and Research Centre, Polish Register of Shipping and other centres [38].

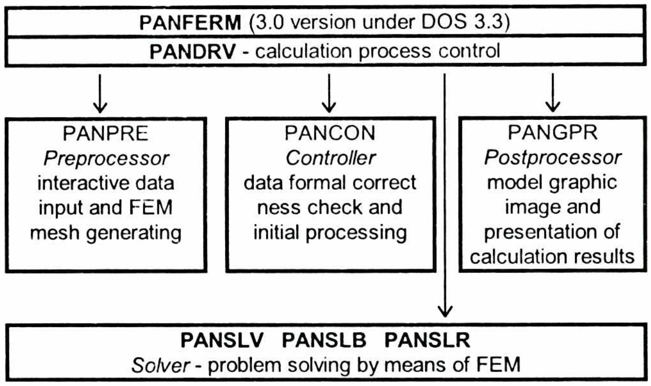


Fig.7. Scheme of the PANFEM software system [38]

Investigations of different factors which influence load carrying capacity

The sofware system was used as a research tool in the next area of Prof.Kmiecik's scientific activity, namely influence investigations of ship plate boundary conditions and imperfections on its load carrying capacity. Results of such investigations were presented in many publications of the period from the beginning of the 1980s till the last years of his activity [21,26,29,39,46]. Sample results of the investigations are shown in Fig.8, where the influence of plate initial distortions, identical in the sense of their traditional measure, on the behaviour of the simply supported rectangular plates is demonstrated [26]. Fig.9 presents the influence of plate boundary conditions and initial stresses [29].

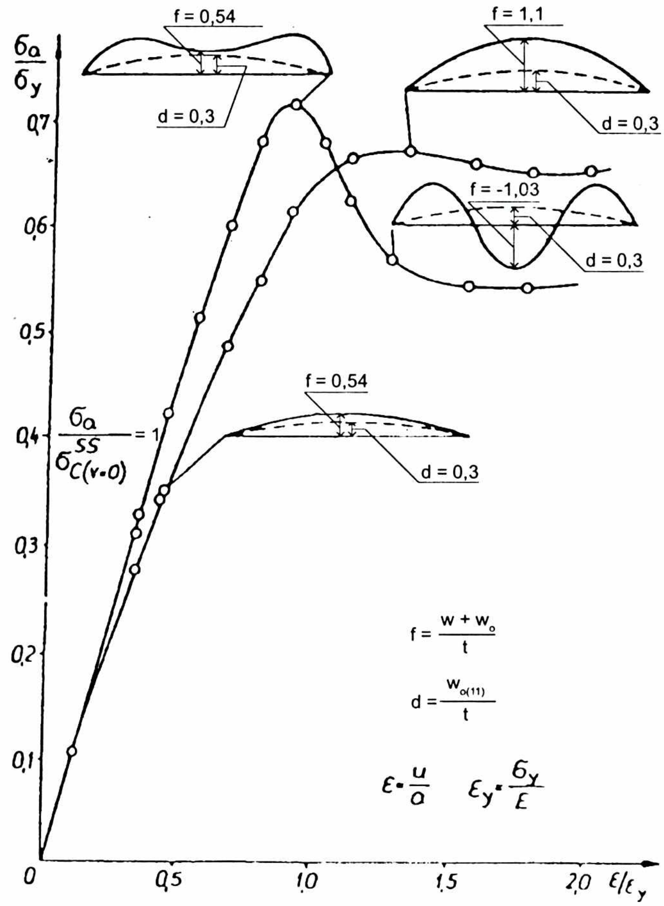


Fig.8. Behaviour of the simply supported rectangular plates with the same initial distortions (in the sense of their traditional measure) [21]

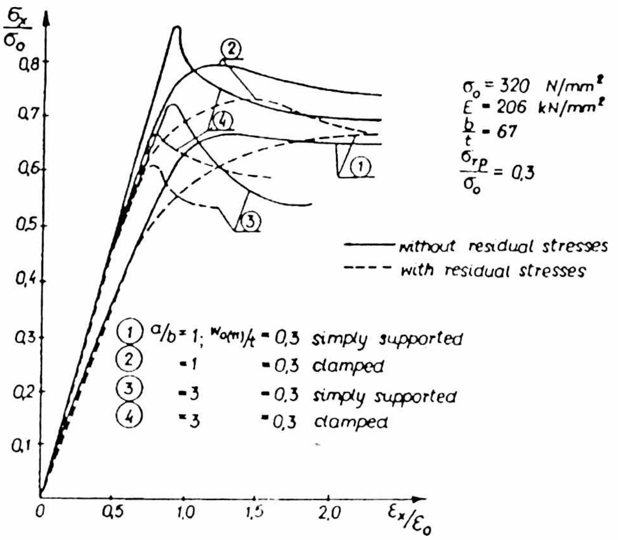


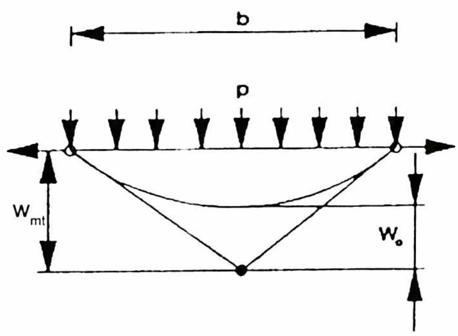
Fig. 9. Influence of plate boundary conditions and initial stresses on behaviour of plates under load [29]

Results of the works in question clearly demonstrated the initial distortion influence on the load carrying capacity of plates as well as confirmed the earlier stated thesis concerning the deflection form as the decisive factor of the influence. They also revealed the strong influence of plate boundary conditions on its behaviour and ultimate capacity under load.

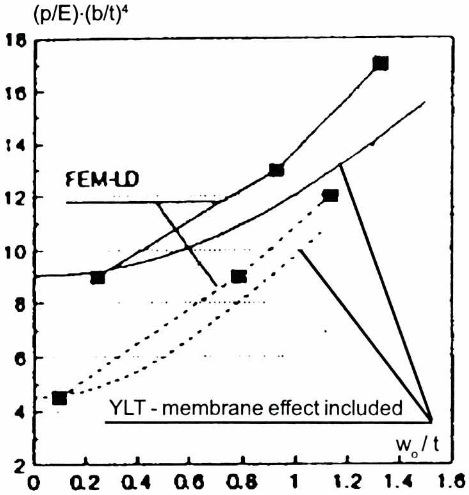
Results of Prof.Kmiecik's numerical investigations on the ultimate capacity of plate structures were recapitulated in his publications of the 1990s [45,46,49].

Investigation on the applicability of plastic hinge (yield line) approach to ship plate structures

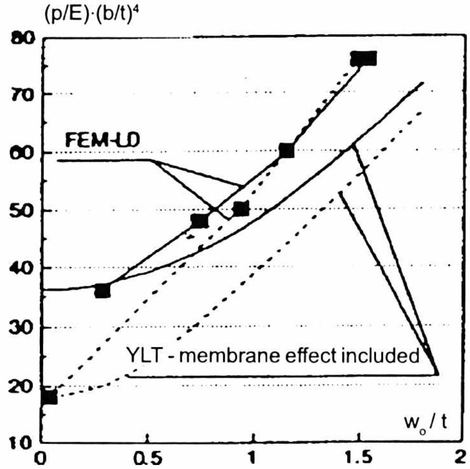
Is was rather a narrow, but characteristic, tide of Prof.Kmiecik's research activity. The criticism of Prof.Kmiecik to common rules and ideas being often used both in the theory and practice, well known to his collaborators, motivated him very frequently to undertake research on a given theme. One of such problems was the applicability to ship structures of the plastic hinge theory used in other branches of structural design. Prof.Kmiecik presented his first thoughts on the theme during the scientific seminars held in Szczecin and Gdańsk in 1990 as well as at the EUROMECH International Conference in 1991. A summary of his investigations can be found in [51] where results are compared of the numerical calculations of the load carrying capacity of rectangular plates under lateral load, performed with the use of three methods: the large deflection theory, small deflection theory and plastic hinge approach. The comparison demonstrated that only the first method yielded the correct calculation results; it was also shown (see Fig.10 according to [51]) that the plastic hinge approach is not applicable to typical ship plate load- carrying capacity problems.



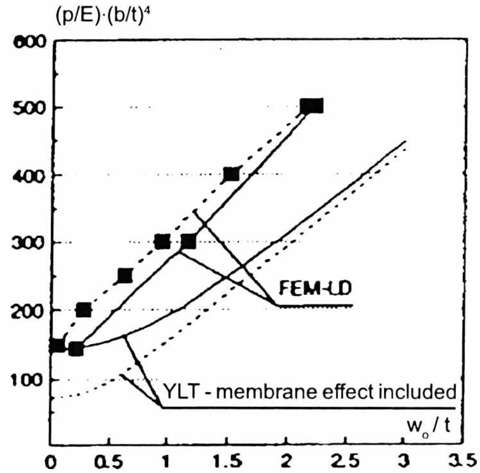
a) Load and deformation scheme



b) Square plates: b/t = 25, β = 0.868
---- simply supported —— clamped



c) Square plates: b/t = 50, β = 1.735
---- simply supported —— clamped



d) Square plates: b/t = 100, β = 3,470
---- simply supported —— clamped

Fig. 10. Square plate load-carrying capacity under lateral load. Comparison of the calculation results obtained by means of the plastic hinge (yield line) theory, marked: „ YLT", and FEM - large deflection theory, marked:„ FEM - L" [51]

PROBABILISTIC APPROACH TO ULTIMATE CAPACITY OF PLATES

Prof.Kmiecik associated his last scientific plans with the research trend undertaken by him at the beginning of the 1990s. But the research works on real ship plate distortions, commenced in the 1970s, were a basis for it. The research on application of the probabilistic approach to plate load-carrying capacity was developed by him during his several month stay in Portugal in 1991 and 1992, results of which concerning the ultimate capacity of rectangular plates can be found in [44, 47]. Stochastic simulation was applied to plate initial distortions and, in result, the statistical distribution of post-welding distortions, of the form typical of ship plates, was obtained. Material strength properties were simulated by means of the Monte-Carlo method. These data were used for the numerical calculations of the plate capacity with the use of the software system already mentioned. It was demonstrated in result of these investigations that the uncertainties in plate strength determination strongly depended on the plate slenderness values and that the relationship was the strongest for the moderately slender plates and was weaker for thick and very thin ones. The relationships are exemplified in Fig.11.

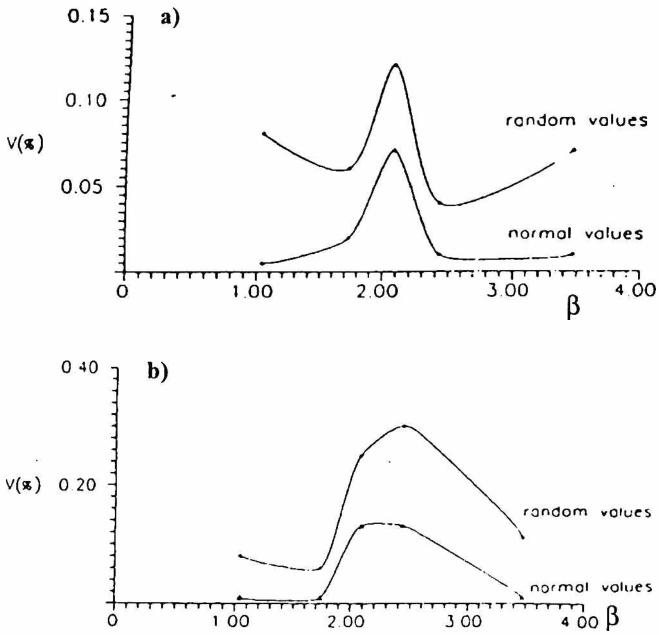


Fig.11. The statistical coefficient of variation V [%] determined for the set of the simulated values of the load carrying capacity of: a) the square plates, b) the rectangular plates of a/b=3, versus the plate slenderness β [47]

Prof.Kmiecik planned to extend the research work and therefore was looking for the graduates willing to prepare doctor's thesis and deepen knowledge in this field. He also thought of undertaking his own works in the area.

SYNTHESIS OF THE RESEARCH WORKS

Several times Prof.Kmiecik made attempt to summarize the results of his scientific works. Some publications dealing with that were already mentioned earlier.

The first synthesis was prepared by him on the basis of the experimental and analytical investigations on the plate ultimate capacity carried out in Trondheim [2,3,4], as early as in 1971. The next occasion to recapitulate his research works in question was the procedure for qualifying him as assistant professor [21] in 1982, which contained results of the analytical investigations in the area of the large deflection theory of imperfect plates, results from the first phase of the numerical calculations as well as the first synthesis of the works on rational backgrounds for establishing distortion tolerances for ship plating.

One of the most important publications containing synthesis of his works was that published by Lloyd's Register in 1986 [28]. It summarized the results of his analyses of plate distortion tolerances, statistical identification of plate deformations, numerical investigations of different factors which influence the plate ultimate capacity as well as results of the experimental research in question.The synthesis of his opinions on the load carrying capacity of the plates being the integral parts of the ship hull structure and on the ultimate capacity of the ship hull considered as a thin walled beam under bending and twisting loads was contained in [35] of 1989. It was mentioned earlier that Prof.Kmiecik paid much attention to keeping continuous contact with the industrial practice and made many efforts to implement results of his scientific works to the practice.

Therefore some of his publications, e.g. [31,32,42], are devoted to the presentation of the ultimate capacity problems in a synthetical and practical way to made them familiar to ship hull designers and demonstrate the advantages of the approach in designing of hull structures.

CLOSING COMMENTS

It was not any intention of the author of the presentation paper to fully review the entire scientific activity of Prof.Kmiecik. Such summary would exceed the scheme of the conference. Therefore only the most important conclusions and selected examples contained in the works of Prof. Kmiecik, were included into the paper. The most important articles and internal publications of Prof.Kmiecik dealing with the problems in question are listed in the *Bibliography*. The full list of his works is included in the Conference proceedings.

Acknowledgements

The author is very grateful to all the *pleno titulo* persons who assisted in collecting many works of Prof.Kmiecik and elaborating the text of the paper.

NOMENCLATURE

- a - plate length
- a/b - plate aspect ratio
- b - plate width
- b/t - plate slenderness
- E - Young's modulus
- N - number of plates in a sample
- p - plate uniform lateral pressure
- p_{c} - critical axial load of initially flat plate
- %pdf - frequency
- p_x - axial external load of plate
- r_{LA} - plate aspect ratio coefficient
- t - plate thickness
- u - axial deflection of plate
- u_{11}, u_{31} - components of total initial deformation of plate
- V(%) - coefficient of variation
- w - elastic deflection of plate
- w_{m} - maximum total deflection at the centre of plate
- w_0 - initial lateral deflection at the centre of plate
- $\overline{w}_0$ - mean value of w_0
- w_{ob} - buckling mode component deflection
- w_{0max} - plate maximum deflection
- $w_{0(11)}$ - double Fourier series coefficient
- x(95) - limit value for 95% of examined plates
- $\overline{x}$ - mean value
- β - plate slenderness
- $\varepsilon, \varepsilon_y$ - axial strains of plate
- $\varepsilon_x, \varepsilon_0$ - total and yield compressive strain, respectively
- η - scale coefficient
- λ - shape coefficient
- σ - standard deviation
- σ_a - axial compressive stress
- σ_e - effective stress
- σ_0, σ_y - yield stress
- σ_{rp} - compressive residial stress
- σ_x - compressive stress
- $\sigma^{ss}_{c(w=0)}$ - critical stress of simply supported plate having very small initial deflection

Logo of the Symposium
on Ship Structure and Mechanics:
"Ultimate Capacity of Ship Structures"
held in memoriam of Prof. Marian Kmiecik

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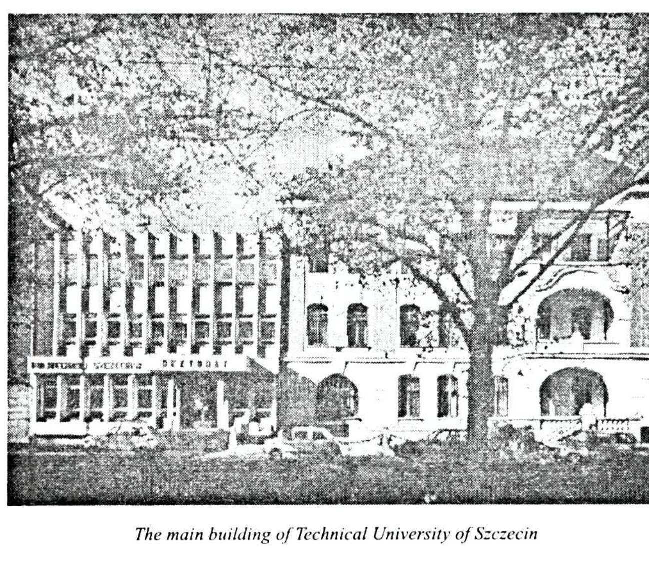

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