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Longitudinally stiffened plate panels under lateral and axial loads (ship bottom plating), Final Report, August 1969.

A. Ostapenko

Built-Up Members in Plastic Design

FINAL REPORT ON RESEARCH PROJECT

LONGITUDINALLY STIFFENED PLATE PANELS UNDER LATERAL AND AXIAL LOADS (SHIP BOTTOM PLATING)

by

Alexis Ostapenko

Naval Ship Engineering Center Contract N00024-67-C-5243

Project Serial No. SF 103-03-01, Task 1974

Fritz Engineering Laboratory

Department of Civil Engineering

Lehigh University

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1. INTRODUCTION

This project was started at Fritz Engineering Laboratory under the title "Built-Up Members in Plastic Design" in 1955. The project may be considered to be an offshoot of a group of projects dealing with plastic design of steel structures made of rolled sections. It was considered that in some areas, notably in ship construction, many structural members are not rolled but built-up by welding from elementary components, such as plates and simple rolled shapes. Thus, in order to utilize the advantages of plastic design, it was necessary to investigate the special conditions which may arise due to the deviation of the built-up cross-sectional shapes from the standard wide-flange shapes and due to the presence of residual stresses produced by welding rather than by rolling. Other aspects of interest were: 1) the combinations of loading, such as shear and thrust, which were considered to be more significant in built-up members, 2) cutouts, and 3) the use of plates which may buckle prior to the attainment of the ultimate load of the whole member.

Most conveniently, the project effort can be divided into two parts.

Part I 1955-58

Investigation under the supervision of Dr. Bruno Thurlimann of wide-flange type sections and of the stability of stiffened panels. This part comprises Phases I to V listed in the next chapter (Chapter 2).

Part II 1958-69

Investigation under the supervision of Dr. Alexis Ostapenko of the ultimate strength of longitudinally stiffened panels subjected to normal and axial loading. This part covers Phase VI as described in Chapter 2.

Except for some brief comments on Part I in connection with the listing of the Phases in Chapter 2, this report describes Part II. The general objectives of this Part are given in Chapter 2. An essay type description of the work conducted after 1958 is given in Chapter 3. The reasons for the particular studies undertaken are stated and the results with corresponding reports are indicated. The final practical product of this research was a nomographic means for designing and analyzing longitudinally stiffened plate panels subjected to axial and normal loads and having plate width-to-thickness ratio (b/t ratio) such that the plate may go into the post-buckling range before the ultimate strength of the panel is reached. The theory was adequately substantiated by tests.

Conclusions of this study and recommendations for future research are presented in Chapter 4. All research workers who participated on this project are listed in Appendix 1, and the list of the reports issued is given in Appendix 2.

2. OBJECTIVES AND RESEARCH PHASES

The general objective of the project was to investigate some specific problems associated with the application of the principles of plastic design and ultimate strength to members built-up by welding from simple rolled shapes and plates, in particular, of the type encountered in ship structures.

The objective of the major portion of the project (Part II-Phase VI) was to develop a method based on the ultimate (plastic) strength for analyzing and designing longitudinally stiffened plate panels subjected to normal and axial loading. The primary interest was in panels and loads as used for ship bottom plating of ships of longitudinal construction.

In the following, the research phases as originally formulated are listed with appropriate comments on their completion.

Part I of the project covered the period from January 1955 till June 1958. It constituted the following phases:

Phase		Report No.
I	Initial Studies Analysis and tests to determine the influence of shear and thrust on plastic capacity of W-type sections	248.1
II	Corner Connections with Cut-Outs Some theoretical results of this study are presented in "Welded Continuous Frames and Their Components, Summary Report 1957", Fritz Engrg. Laboratory Iterim Report No. 38, December 1957. The work was then abandoned in favor of completing Phase V.	248.3 (not completed)

Phase		Report No.
III	Deep Girders This study was taken over by Project 251 "Welded Plate Girders" and the work was completed there.	
IV	Stiffening Requirements of Flanges and Corners This topic was absorbed by other projects in which some particular cases were investigated. No general study has been performed.	
V	Effective Width of Buckled Deck Plates A theoretical study was carried out of the buckling in the elastic or strain-hardening range of edge loaded plates with transverse or longitudinal stiffeners.	248.2

Part II, started in 1958, constituted the last general phase of the project (Phase VI).

VI	Ultimate Strength of Longitudinally Stiffened Plates Subjected to Normal and Axial Loads The principal purpose of this part was to investigate the ultimate strength and develop a design method. The approach and the scope were re-evaluated from year to year in the light of the latest findings and the immediate needs of the sponsor. The general purpose however remained unchanged. An essay type outline of the work on this phase is presented in the next chapter.	248.4 to 248.28

3. OUTLINE OF RESEARCH PART II (1958-69)

3.1 Pilot Tests on Stiffened Panels

Prior to the initiation of this research, the behavior of stiffened panels subjected to normal and axial loads has been studied only in the elastic range and almost exclusively considering small deflections. To obtain some insight into the behavior and modes of failure of such panels when they go into the plastic range, a pilot test program was initiated by this project in 1958. Five panel specimens fabricated as one-quarter models of typical ship bottom plating were tested. The loaded ends were simply-supported (pinned) with the side edges being free. A special fixture was designed to simultaneously apply normal and axial loading (248.4, 248.6)*. The variable parameters were the intensity of normal loading (0, 6.5 and 13 psi) and the plate width-to-thickness ratio (b/t = 60 and 40). The test results pointed to the importance of the welding residual stresses and of the restraint furnished by the stiffeners (248.4).

3.2 Plate Behavior under Normal and Edge Loading

Some tentative ideas about the effect of residual stresses on the buckling of panels and their design were developed (248.8). However, more had to be known about the behavior and strength of unstiffened plates subjected to normal and edge loads before more ac-

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*Numbers in parentheses indicate the reports issued on the research just discussed. All reports are listed in Appendix 2.

accurate methods could be evolved for stiffened panels. A theoretical study then was conducted which indicated that the normal load of the intensities considered has a relatively small effect on the axial strength of the plate (248.7). In fact, it may strengthen the plate and thus it would be safe to assume that the plate in a panel behaves as if it were subjected to axial loading alone. However, the large-deflection post-buckling behavior of the plate in the inelastic range must be considered.

3.3 Residual Stresses and Compressive Material Properties

An experimental program served to arrive at the magnitude of the residual stresses before and after welding and to study their effects on the buckling and ultimate strength of stiffened panels. The rotational restraint provided by the stiffeners was also varied. Five specimens were tested. (248.5)

Concurrently, tests were conducted to determine the compressive properties of the steel used in the specimens. This was necessary in order to take into account the actual material properties in analyzing the panel test results; only tensile coupon tests had been performed previously. A special testing technique was developed. The compressive yield stress was found to be consistently higher than the tensile yield stress by about nine percent. (248.10)

3.4 Tests on Fixed-End Panels

Since the actual ship plating is continuous over the transverses, the ends of the panels are restrained elastically with pinned and fixed supports being the lower and upper bounds. Only pinned support was used in the two above described test programs (248.4 and 248.5). Thus, it was desirable to explore the behavior of the panels with the loaded edges fixed. The test fixture was accordingly modified, and five specimens fabricated. One of these was used to determine the residual stresses and four were tested analogously to the pin-ended specimens. The plate width-to-thickness ratio was 60; thus, the plate was invited to buckle. The normal loading was again 0,6.5 and 13 psi. Unlike the pinned-end panels, the fixed-end panels did not reach their ultimate load at the point of plate buckling; they exhibited substantial post-buckling strength as well as a more gradual post-ultimate load drop-off. Another important conclusion of this program was that a simplified non-distructive method of measuring residual stresses can give very reliable accuracy, and could be recommended for future research or practical use. (248.12)

3.5 Design Nomographs-Low b/t

Theoretical studies indicated that the behavior of longitudinally stiffened plate panels under normal and axial loads is analogous to that of beam-columns if the effects of yielding, plate buckling, and post-buckling responses are properly taken into account. A simpler, nevertheless very important in ship building, case is when the plate has sufficiently low width-to-thickness ratio (less than about 40) not to buckle before the ultimate strength of the panel is reached. The panel then can be analyzed considering plastification only without regard to buckling. A computer program was developed to perform such an analysis (248.16). The method correlated quite well with test results. Yet the program was too cumbersome for design use. The numerical output for a variety of geometrical, loading, and material parameters was then studied to find some patterns of interaction. It was thus possible to arrive at a combination of design nomographs which permitted a direct determination of the required thickness and consequently of all other panel dimensions, such as, spacing and dimensions of the stiffeners, for a prescribed set of overall panel width and length, loading and material yield stress. One nomograph was for pinned-end panels, and the other for fixed-end panels. (248.13)

3.6 Design Nomographs-Large b/t

Meanwhile, a literature search was conducted to find what was known from theory and experiments about the post-buckling and post-ultimate behavior of individual plates subjected to edge compression. An equation for the elastic post-buckling behavior which had the best correlation with the few tests available was selected (the study described in Part 3.2 was too limited). Due to a complete absense of any theoretical or experimental data, intuitively plausible assumption was made for the post-ultimate behavior of the plate. Thus, a continuous relationship was established between the average stress and the edge strain for plates in the post-buckling range. (248.15)

This relationship was then utilized in a computer program for determining the ultimate strength in which the plate may buckle before the ultimate strength of the whole panel is reached (248.14 and 248.20).

Considerable difficulties were encountered in systematizing the numerical computer output into design nomographs. Finally, a somewhat less flexible set than for low b/t was developed --- it was limited to a specified yield stress of 47 ksi. (248.14, 248.19)

3.7 Post-Ultimate Plate Behavior and General Computer Program

Although the nomographs were completed, a nagging doubt still remained about the validity of the accuracy of the assumption for the post-ultimate plate behavior. An unsuccessful attempt was made to investigate this range theoretically by means of a lumped parameter formulation (248.21). Then an experimental exploration was planned and a test fixture designed (248.25). Unfortunately, this attempt had to be abandoned due to the limitations in time and funds.

It was decided then to extend the existing programs to other materials than steel, in fact, to any material for which the average stress-versus-edge strain relationship is available. A comprehensive, well documented and easy to use program evolved. (248.23)

This program was then employed to study the effect on the ultimate strength of longitudinally stiffened panels if the plate behaved differently than assumed in developing the design nomographs. A series of different patterns was assumed. For some combinations of geometries and loads the devitation was quite substantial. However, for the range common to ship bottom plating the effect of changing the plate behavior pattern from the original one was acceptably insignificant. This study thus showed that the nomographs may be employed with confidence for practical purposes. (248.24)

4. SUMMARY AND RECOMMENDATIONS FOR FUTURE RESEARCH

4.1 Summary

Part I of the project (1955-58) gave solutions to some of the initially formulated phases: Phases I and V. Phases II, III, and IV were either abandoned or absorbed by other projects. (The listing of the phases and their status is given in Chapter 2).

Part II (1958-69) dealt with an investigation of the ultimate strength of longitudinally stiffened steel plate panels under normal and axial loads and developing a design method for such panels. A method of analysis well verified by experimental results was developed and several computer programs written. Two sets of design nomographs were worked out which require about 5-10 minutes per trial design. One set is for plates with low b/t (b/t less than abt. 40, plate does not buckle) and the other set is for plates with large b/t (b/t greater than abt. 40, plate may buckle before the ultimate strength of the whole panel is reached). The latter set of nomographs was limited to the steels with the yield stress equal to 47 ksi.

4.2 Recommendations for Future Research

Except as noted in connection with Part I, all major objectives of the project have been completed. However, in the course of work on the project it became apparent that some of the abandoned topics are still very important and need to be investigated, and that some items may need further extension. The most important of these are listed below as recommendations for future research together with some new areas related to the theme of the project.

1) Corner Connections with Cut-Outs

This is Phase II of Part I on which some work was done but was later abandoned. Since the problem of the strength of transverse ship hull frames with cut-outs in the corners (for passageways and the like) is still of great actuality, this topic is recommended for future research.

2) Post-Buckling and Post-Ultimate Behavior of Rectangular Plates under Edge Loading

Although the major assumption on which the nomographs for panels with large b/t are based was found to have insignificant influence on the results when the geometric proportions and loads typical for ship structures are used, this may not be true for very light craft or for some special purpose structures. Thus, the true behavior must be established. Some initial work in this direction has been performed on the project or elsewhere and it can serve as the starting point, but considerably more exact and more comprehensive effort is needed. For example, residual stresses and initial imperfections should be accurately taken into account. The work should be also extended to cover non-linear materials, such as, aluminum alloys, fiber-reinforced plastics, etc.

3) Panels with Angle Stiffeners

Research so far has been limited to panels with Tee-stiffeners which for ordinary proportions deflect in the plane of the stems and are not expected to twist before the ultimate load is reached. More convenient and economical from the constructional point of view are angle stiffeners. The big drawback in their use is that they tend to twist as soon as the loading is applied and their behavior and its effect on the plating are essentially unknown, especially in the inelastic range. Thus, a thorough investigation is needed before angle stiffeners could be utilized for panels designed on the ultimate strength basis.

4) Longitudinally Stiffened Plate Panels under Dynamic Loads

All the research conducted on this project has been limited to statically applied loads. Thus, the results are valid only if the loads change their magnitude very gradually or when it is known how to replace a dynamically applied load (impact, vibration) with an equivalent statical load. Some rules for this purpose have been established, but essentially all of them assume that the structure responds linearly. This is not valid if ultimate strength approach is to be considered. Thus, the ultimate strength behavior of longitudinally stiffened plate panels subjected to dynamically applied axial and normal loads must be investigated.

5. ACKNOWLEDGEMENTS

The author wishes to express his gratitude on behalf of all of the project research staff to the Naval Ship Engineering Center (formerly the Bureau of Ships), USN, for the financial support of this project. In particular, Mr. John Vasta is thanked herewith, whose interest in this research area gave the initial impetus to the project and whose sustained encouragement contributed to the success. He and his staff exercised effective technical control throughout the duration of the project. The following members of his staff, among others, gave special attention to this task: Messrs: Joseph P. Banko, James Seijd, Donald S. Wilson, and Elias R. Ashey.

This project, together with several others under the title Welded Continuous Frames and Their Components, received general guidance from the Lehigh Project Subcommittee of the Structural Steel Committee of the Welding Research Council. Dr. Theodore R. Higgins has been Chairman of the Subcommittee and Mr. Charles F. Larson, Secretary. The complete list of the subcommittee members is given in Appendix 3. We appreciate their help.

All the research personnel were drawn from the Department of Civil Engineering with all theoretical and experimental work performed in Fritz Engineering Laboratory. Currently, Dr. David A. VanHorn is Chairman of the department and Dr. Lynn S. Beedle is Director of the laboratory. At the time when the project started and for a number

of years afterwards, Professor William J. Eney was Head of the department and Director of the Laboratory. Invaluable contribution to the success of the project was made by the supporting personnel of the laboratory, consisting of technicians, machinists, draftsmen, and clerical staff.

All contractual arrangements have been handled very efficiently by the Office of Research of Lehigh University under the direction of Dr. George R. Jenkins. The project staff, and especially the project director, are very grateful for their ready assistance.

6. APPENDICES

APPENDIX 1 RESEARCH PERSONNEL

The following persons have been engaged on this research project. The period which each was associated with the project is indicated in parentheses.

Bott, Bruce A. (2/66-6/66)
Davidson, Hugh L. (4/64-6/65)
Kondo, Jun (7/61-9/65)
Kusuda, Tadao (1/55-6/58)
Lee, Ti-ta (8/58-9/61)
Lopez, Leonard A. (8/66-8/67)
Ostapenko, Alexis (1958-69)
Rampetsreiter, Robert H. (9/60-6/62)
Rutledge, Donald R. (2/67-10/68)
Strawbridge, Randall A. (8/65-8/66)
Thurlimann, Bruno (1/55-1/60)
Tsuiji, Tsuneo (9/64-6/65)
Vojta, Joseph F. (9/65-8/67)

In addition to the above listed, the following participated as administrative directors during the transition period in 1960 and 1961.

Beedle, Lynn S.
Driscoll, George C., Jr.

APPENDIX 2 LIST OF REPORTS

F.E.L. Report No.	Author(s) - Title - Date	Distribution
248.1	T. Kusuda and B. Thurlimann STRENGTH OF WIDE-FLANGE BEAMS UNDER COMBINED INFLUENCE OF MOMENT, SHEAR AND AXIAL FORCE, May 1958.	Full distribution*
248.2	T. Kusuda BUCKLING OF STIFFENED PANELS IN ELASTIC AND STRAIN HARDENING RANGES, Ph.D. Dissertation, June 1958. Published as Report No. 39 of Transportation Technical Research Institute, Tokyo, October 1959.	Full distribution
248.3	B. Thurlimann and T. Kusuda CORNER CONNECTIONS WITH CUT-OUTS (This work was abandoned in favor of completing F.E.L. Report No. 248.2 before T. Kusuda's leaving Fritz Laboratory).	
248.4	A. Ostapenko and Ti-ta Lee TESTS OF LONGITUDINALLY STIFFENED PLATE PANELS SUBJECTED TO LATERAL AND AXIAL LOADING, August 1960.	Full distribution
248.4A	Supplement to 248.4; same authors, title, date; subtitle: STRAIN AND DIAL GAGE READINGS	To sponsor and requestors
248.5	R. H. Rampetsreiter, Ti-ta Lee, and A. Ostapenko TESTS ON LONGITUDINALLY STIFFENED PLATE PANELS --- Effect of Residual Stresses and Rotational Restraint by Stiffeners, July 1962.	Full distribution
✓248.5A	Supplement to 248.5, same authors, title, date; subtitle: STRAIN AND DIAL GAGE READINGS	To sponsor and requestors
248.6	A. Ostapenko APPARATUS FOR TESTING PLATE PANELS UNDER AXIAL AND LATERAL LOADING, June 1961.	To sponsor and committee

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*"Full distribution" means that the report was distributed to the sponsor government agencies, committee, and all interested in this research.

F.E.L. Report No.	Author(s) - Title - Date	Distribution
248.7	Ti-ta Lee ELASTIC-PLASTIC ANALYSIS OF SIMPLY SUPPORTED RECTANGULAR PLATES UNDER COMBINED AXIAL AND LATERAL LOADING, Ph.D. Dissertation, August 1961 (Available from University Microfilms)	Full distribution
248.8	A. Ostapenko SCANTLINGS OF LONGITUDINALLY STIFFENED SHIP BOTTOM PLATING --- TENTATIVE IDEAS ON A DESIGN METHOD, April 1961	To sponsor
248.9	Ti-ta Lee and A. Ostapenko PROGRESS REPORT ON THE TESTS CONDUCTED DURING 1960, December 1960	To sponsor and committee
√248.10	R. H. Rampetsreiter COMPRESSIVE PROPERTIES OF THIN STEEL COUPONS M.S. Thesis, May 1962.	Full distribution
248.11	A. Ostapenko and J. Kundo PROGRESS REPORT ON TESTS WITH FIXED LOADING EDGES AND MEASUREMENT OF RESIDUAL STRESSES, November 1962	To sponsor and committee
248.12	J. Kondo and A. Ostapenko TESTS ON LONGITUDINALLY STIFFENED PLATE PANELS WITH FIXED ENDS, July 1964.	Full distribution
248.12A	Supplement to 248.12; same authors, title, date; subtitle: STRAIN AND DIAL GAGE READINGS	To sponsor and requestors
248.13	Jun Kondo ULTIMATE STRENGTH OF LONGITUDINALLY STIFFENED PLATE PANELS SUBJECTED TO COMBINED AXIAL AND LATERAL LOADING (Low b/t), Ph.D. Dissertation, August 1965. Also available from University Microfilms)	Full distribution
248.14	T. Tsuiji STRENGTH OF LONGITUDINALLY STIFFENED PLATE PANELS WITH LARGE b/t, M.S. Thesis, June 1965.	Full distribution
248.15	H. L. Davidson POST-BUCKLING BEHAVIOR OF LONG RECTANGULAR PLATES, M.S. Thesis, June 1965.	Full distribution
248.16	B. A. Bott, J. Kondo and A. Ostapenko COMPUTER PROGRAM FOR ULTIMATE STRENGTH OF LONGITUDINALLY STIFFENED PANELS (small b/t), May 1966.	Full distribution

F.E.L. Report No.	Author(s) - Title - Date	Distribution
248.17	B. A. Bott and A. Ostapenko COMPUTER PROGRAM FOR SEQUENCING TABULATED DATA, June 1966	Full distribution
248.18	J. F. Vojta and A. Ostapenko ULTIMATE STRENGTH DESIGN OF LONGITUDINALLY STIFFENED PLATE PANELS WITH LARGE b/t, (J. F. Vojta's M.S. Thesis), August 1967.	Full distribution
248.19	J. F. Vojta and A. Ostapenko ULTIMATE STRENGTH DESIGN CURVES FOR LONGITUDINALLY STIFFENED PLATE PANELS WITH LARGE b/t, August 1967	Full distribution
248.20	J. F. Vojta COMPUTER PROGRAM FOR ULTIMATE STRENGTH OF LONGITUDINALLY STIFFENED PANELS (Large b/t) August 1967.	Full distribution
248.21	L. A. Lopez DESCRIPTION OF THE INPUT FOR THE ELASTIC-PLASTIC PLATE PROGRAM, August 1967.	To sponsor and project staff
248.22	A. Ostapenko TESTING OF STIFFENED PLATES UNDER COMBINED AXIAL AND LATERAL LOADING, June 1966	To sponsor
248.23	D. R. Rutledge COMPUTER PROGRAM FOR ULTIMATE STRENGTH OF LONGITUDINALLY STIFFENED PANELS (Large and small b/t, General Material Properties), July 1968.	Full distribution
248.24	D. R. Rutledge and A. Ostapenko ULTIMATE STRENGTH OF LONGITUDINALLY STIFFENED PLATE PANELS (LARGE AND SMALL b/t, GENERAL MATERIAL PROPERTIES), (D. R. Rutledge's M.S. Thesis), September 1968.	Full distribution
248.25	D. R. Rutledge TEST FIXTURE FOR RECTANGULAR PLATES IN POST-BUCKLING RANGE, March 1969.	To sponsor and requestors
248.26**	A. Ostapenko ANALYSIS OF LONGITUDINALLY STIFFENED PLATE PANELS USING DESIGN NOMOGRAPHS (LARGE b/t), (First Draft), December 1967.	To sponsor (supplement to 248.18 and 248.19)

** Report 248.26 was at first numbered 248.22

F.E.L. Report No.	Author(s) - Title - Date	Distribution
248.27	A. Ostapenko ULTIMATE STRENGTH ANALYSIS OF LONGITUDINALLY STIFFENED PLATE PANELS, October 1968. (Text of oral presentation at the ASCE Annual Meeting in Pittsburgh, Sept. 30-Oct. 4, 1968).	To project staff
248.28	A. Ostapenko FINAL REPORT ON RESEARCH PROJECT, LONGITUDINALLY STIFFENED PLATE PANELS UNDER LATERAL AND AXIAL LOADS (SHIP BOTTOM PLATING), August 1969.	Full distribution

APPENDIX 3 LIST OF MEMBERS OF LEHIGH PROJECT SUBCOMMITTEE

The following have served on Lehigh Project Subcommittee, Structural Steel Committee, Welding Research Council

Theodore R. Higgins, Chairman
John H. Adams
Arsham Amirikian
Lynn S. Beedle
Carson F. Diefenderfer
*Frederick H. Dill
Samuel Epstein
Edward R. Estes
Ivo Fioriti
Gerard F. Fox
Theodore V. Galambos
Edwin H. Gaylord
John A. Gilligan
LaMotte Grover
Ira Hooper
William H. Jameson
Bruce G. Johnston
*Jonathan Jones
Thomas C. Kavanaugh
Robert L. Ketter
Kenneth H. Koopman
Carl Kreidler
*Heathcote W. Lawson
Harold Liebowitz
John N. MacAdam
Edward M. MacCutcheon
William A. Milek
Nathan M. Newmark
Nicholas Perrone
Emanuel Pisetzner
Robert M. Stuchell
John Vasta
Ivan M. Viest
Charles F. Larson, Secretary

*Deceased

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13. ABSTRACT

A final summary is presented of the work performed on this research project from 1955 till 1969. A theory was developed for determining the ultimate strength of longitudinally stiffened plate panels subjected to normal and axial loads. Fifteen panel specimens were tested. Computer program output was used to develop design nomographs for panels with pinned or fixed loaded ends. Dimensions and loads were typical for ship bottom plating. The following effects were included: welding residual stresses, post-buckling and post-ultimate plate behavior, different materials in stiffeners and plate. Lists are given of all research workers and of all technical reports issued by the project.

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II. SF 103-03-01, Task 1974

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KEY WORDS
stiffened plate, combined loading, axial loading, normal loading, ships, ultimate strength, design method, final summary report

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