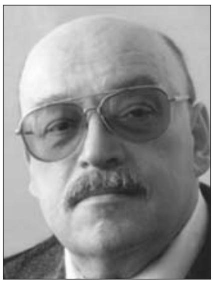
УДК 629.021
Г75

ASSESSMENT OF RIGIDITY OF THE DESIGNED INTERMITTENT CONNECTIONS IN SHIP STRUCTURES

ОЦЕНКА ЖЕСТКОСТИ ПРОЕКТИРУЕМЫХ ПРЕРЫВИСТЫХ СВЯЗЕЙ СУДОВЫХ КОНСТРУКЦИЙ

DOI 10.15589/SMI. 2018.01.17



Коробанов Юрий Николаевич

Кузнецов Анатолий Иванович

Грабенко Алла Андреевна

Yuriy N. Korobanov Ю. Н. Коробанов, д-р техн. наук, проф.
yuriy.korobanov@nuos.edu.ua
ORC ID: 0000-0002-1017-3939

Anatoliy I. Kuznetsov А. И. Кузнецов, канд. техн. наук, доц.
anatolii.kuznietsov@nuos.edu.ua
ORC ID: 0000-0001-5149-3181

Alla A. Hrabenko А. А. Грабенко, асп.
111016@nuos.edu.ua
ORC ID: 0000-0002-2841-1659

Admiral Makarov National University of Shipbuilding, Mykolaiv

Национальный университет кораблестроения имени адмирала Макарова, г. Николаев

Abstract. The article presents the assessment of rigidity of ship intermittent connections. The stress distribution and the values of rigidity coefficients of intermittent connections of the structure have been studied. The analysis is based on the results of computational procedures which follow the finite and boundary element methods to the contrary of the numerical methods used by other authors who cover the same topic. It has been established that there is a great variance and a lot of allowances in rigidity coefficients, as well as methods for their calculation. An analysis of methods for determining rigidity coefficients has shown that they cannot practically be introduced into the computer-aided system for ship structure design in the form presented in appropriate literary sources. In addition, the paper covers various approaches to interpretation of the rigidity coefficients of intermittent connections and methods for their calculation using the example of a discontinuous plate. It is shown how to apply the finite and boundary element methods with their possible integration into computer-aided design systems.

Keywords: rigidity of intermittent connections; rigidity factor; computer-aided system for ship structure design.

Аннотация. Приведена оценка жесткости прерывистых связей судового назначения. Изучаются распределение напряжений и величины коэффициентов жесткости прерывных связей конструкции. За основу анализа принимаются результаты расчетных процедур методами конечных и граничных элементов в сравнении с численными аналитическими других авторов. Установлено, что коэффициенты жесткости, а также методы их определения сильно различаются между собой, имеют множество допущений. Анализ методов определения коэффициентов жесткости показал, что в таком виде, как они излагаются в литературе, внедрение их в систему автоматизированного проектирования судовых конструкций практически невозможно. Рассмотрены различные подходы к трактовке коэффициентов жесткости прерывистых связей и методы их определения на примере прерывистой пластины. Приводятся пути использования методов конечных и граничных элементов с возможностями их интегрирования в системы автоматизированного проектирования.

Ключевые слова: жесткость прерывистых связей; коэффициент жесткости; система автоматизированного проектирования конструкций судового назначения.

Анотація. Наведено оцінку жорсткості переривчастих в’язей суднового призначення. Вивчається розподіл напружень і значень коефіцієнтів концентрації напружень переривчастих в’язей конструкції. За основу аналізу приймаються результати розрахункових процедур методами кінцевих і граничних елементів порівняно з роботами інших авторів. Встановлено, що коефіцієнти жорсткості, а також методи їх розрахунку дуже різняться між собою, мають велику кількість припущень. Аналіз методів визначення коефіцієнтів жорсткості показав, що в такому вигляді, як вони подані в літературі, впровадження їх в системи автоматизованого проектування суднових конструкцій практично неможливе. Розглянуто різні підходи до тлумачення коефіцієнтів жорсткості переривчастих в'язей, і методи їх визначення на прикладі переривчастої пластини. Наводяться шляхи використання методів кінцевих і граничних елементів з можливостями інтегрування в системи автоматизованого проектування.

Ключові слова: жорсткість переривчатих в'язей; коефіцієнт жорсткості; система автоматизованого проектування конструкцій суднового призначення.

References

[1] Korobanov Yu. N., Lishchuk O. M., Lishchuk I. M. *Analiz predposylok ispolzovaniya metodov granichnykh elementov v sudostroitelnykh sistemakh avtomatizirovannogo proektirovaniya* [Analysis of the prerequisites for the use of boundary element methods in shipbuilding computer-aided design systems]. *Zbirnyk naukovykh prats NUK* [Collection of scientific publications of NUOS]. Mykolaiv, NUOS Publ., 2006, issue 2 (407), pp. 31–38.

[2] Korotkin Ya. I., Rostovtsev D. M., Sivers N. L. *Prochnost korablya* [Ship strength]. Leningrad, Sudostroenie Publ., 1974. 432 p.

[3] Sivers N. L. *Raschet i konstruirovaniye sudovykh nadstroek* [Calculation and construction of ship superstructures]. Leningrad, Sudostroenie Publ., 1966. 298 p.

[4] Kurdyumov A. A. *Prochnost korablya* [Ship strength]. Leningrad, Sudpromgiz Publ., 1956. 384 p.

[5] *Normy prochnosti morskikh sudov. Registr Soyuza SSR* [Standards of strength of sea-going vessels. The Register of the USSR]. Leningrad, Morskoy transport Publ., 1962. 52 p.

[6] Shimanskiy Yu. A. *Proektirovaniye preryvistykh svyazey sudovogo korpusa* [Design of intermittent connections of the ship's hull]. Leningrad, Sudpromgiz Publ., 1949. 316 p.

[7] Shimanskiy Yu. A. *Spravochnik po stroitelnoy mekhanike korablya, tom 3* [Handbook on ship mechanics, volume 3]. Leningrad, Gosudarstvennoe soyuznoe izdatelstvo sudostroitelnoy promyshlennosti Publ., 1960. 799 p.

Problem statement. Design dimensions of the connections of ship structures are conventionally assigned based on the conditions of strength, rigidity and stability. If it is an intermittent structure, the degree of its contribution to the overall strength is usually characterized by such a term as rigidity. In turn, the indicator of a structure's rigidity is the rigidity coefficient.

The coefficient of rigidity of intermittent connections has a completely different interpretation as compared to the one adopted for a continuous structure subject to tension, bending and torsion. The rigidity performance of ship discontinuous structures is assessed judging from the shear stresses and displacements at the junction between discontinuous and continuous parts.

Latest research and publication analysis. Hull structures contain a lot of connections with a limited length and a sharply changing cross section. These connections are called intermittent because they have a substantial effect on the longitudinal or transverse strength of ship structures (depending on their orientation on the ships hull).

A sharp change in cross section of the hull connection or its interruption leads to a redistribution of stresses and change in rigidity. Numerical evaluation of rigidity of a discontinuous structure is performed on the basis of rigidity coefficient that takes into account the effect of the discontinuous part of the structure. In the study of deformation of intermittent ship structures, they are conventionally divided into two components: the section that is continuous over the entire length of the structure and the adjoining discontinuous section, i.e., the one that covers only a part of the structure length. The forces of interaction of these sections are assessed with the provision of equality of the deformations along the line of their junction.

Current requirements for the design of ship structures make a point for employing domestic systems of computer-aided ship design, for instance, as it is suggested in [1].

Many papers consider the design of intermittent ship hull connections [2–7] largely relying upon assessment of their rigidity coefficients. The data they provide is quite contradictory and dissociated in a large number of sources due to the diversity of pairing forms between the discontinuous and continuous parts of the structure.

THE ARTICLE AIM is to generalize and systematize the concept of rigidity coefficient of ship structures, as well as the methods for their assessment.

The analysis of the methods for determining rigidity coefficients has shown that they can hardly be introduced into domestic computer-aided systems for ship structure design in the form presented in appropriate literary sources, since they contain many allowances poorly implemented in the system. Up-to-date numerical methods for the assessment of the stress-strain state of intermittent connections allow for the use of finite element (FEM) and boundary element (BEM) methods [1]. The ultimate goal of this study is to determine the rigidity coefficients of intermittent connections based on numerical methods for the assessment of the stress-strain state of hull structures.

Basic material. Intermittent connections are formed both along and across the ship hull, affecting both the longitudinal and transverse strength of ship hull structures at the same time. A significant place is occupied by superstructures, which are part of the continuous ship hull. The publication [3] deals with the study of the stress-strain state of ship superstructures as a type of intermittent ship structures.

In the study of the stress-strain state of intermittent connections, their discontinuous parts are mentally separated from the continuous part. It is supposed that there are shearing and normal interaction stresses along the line of their junction. These stresses are determined based on the condition that the deformations along the junction line of the discontinuous and continuous parts are equal.

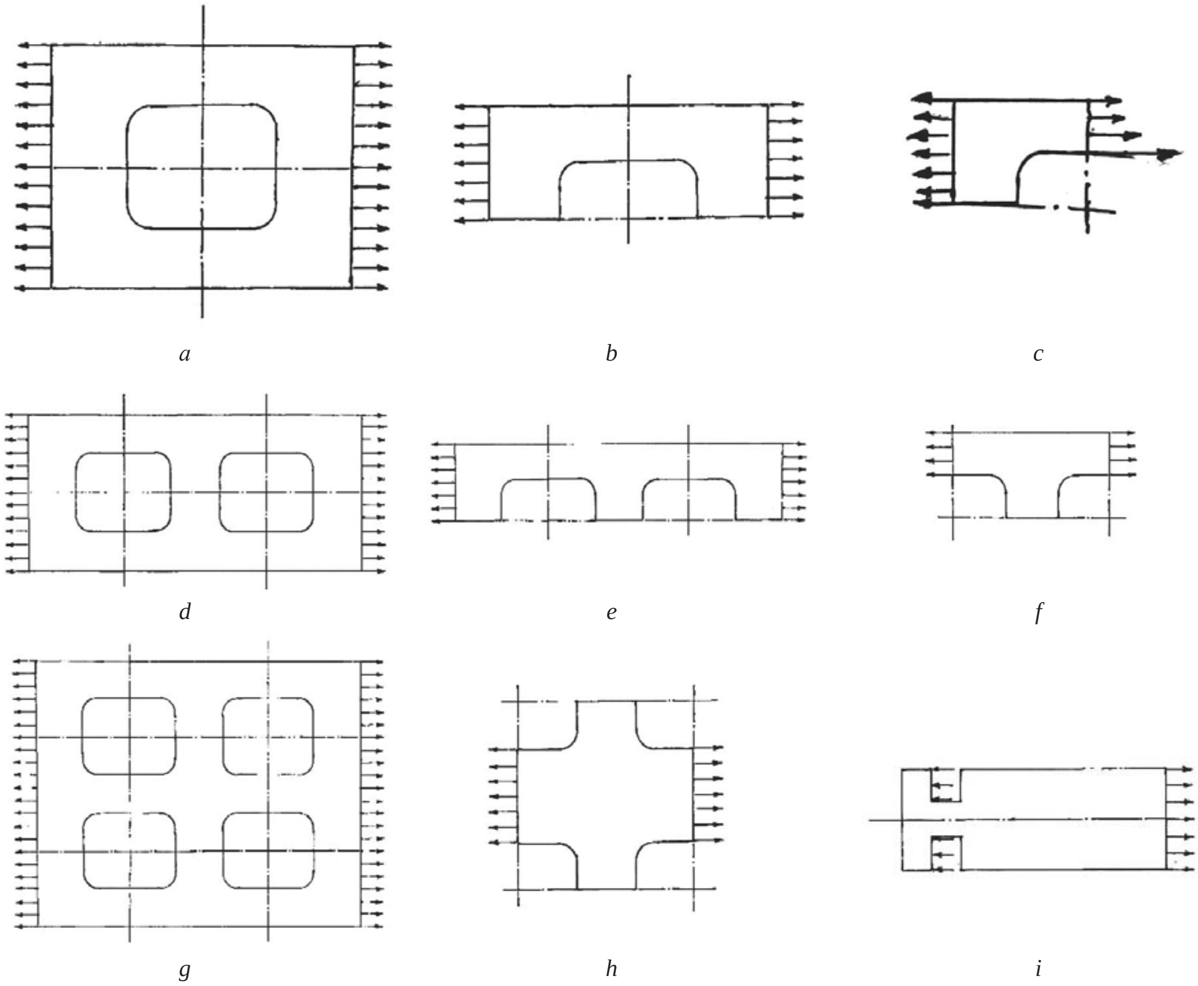
In the first place, one should compare the intermittent ship connections to the structures that have cutouts. In general, intermittent connections are exposed to stretching, bending, and shearing forces. Formation of intermittent connections of the structures with cutouts is shown in Fig. 1. The object of analysis is a ship structure with relatively large cutouts which is subject to stretching. It is clear that the intermittent connections are singled out through splitting the structures along their symmetry axes. Such allocation of intermittent ship connections allows combining the tasks of assessment of the stress-strain state both of the ship structures with large cutouts and of the intermittent ship structures. In turn, this allows for the use of similar mathematical models, calculation procedures, and methods.

As it follows from Fig. 1, the most common pattern is a stretchable plate having a rectangular cutout with rounded corners (see Fig. 1, *a*). Meanwhile, Fig. 1, *b* shows an intermittent structure formed when conditionally splitting the structure along the longitudinal axis of symmetry. Splitting along two axes of symmetry results in an intermittent connection shown in Fig. 1, *c*.

In the plates with two (Fig. 1, *d*) and four cutouts (Fig. 1, *g*), intermittent connections form similarly. For the plate with two cutouts, intermittent connections are shown in Fig. 1, *b* and 1, *c*. For a plate having four cutouts (Fig. 1, *g*), an intermittent connection can take the form shown in Fig. 1, *h*.

Fig. 1, *i* presents an intermittent connection typical for suspended foundations and structures loaded with centripetal forces.

Intermittent connections appear as design solutions devised during the design of hull structures. A brief analysis of these design solutions is shown in Fig. 2.



a *b* *c*

d *e* *f*

g *h* *i*

Fig. 1. Stretching diagrams for plates with various cutouts: *a* — a plate with a single cutout; *b, c* — intermittent connections formed at the presence of a single cutout; *d* — a plate with a double cutout; *e, f* — intermittent connections formed at the presence of a double cutout; *g* — a plate with four cutouts; *h* — an intermittent connection formed by four cutouts; *i* — an intermittent connection under the action of centripetal forces

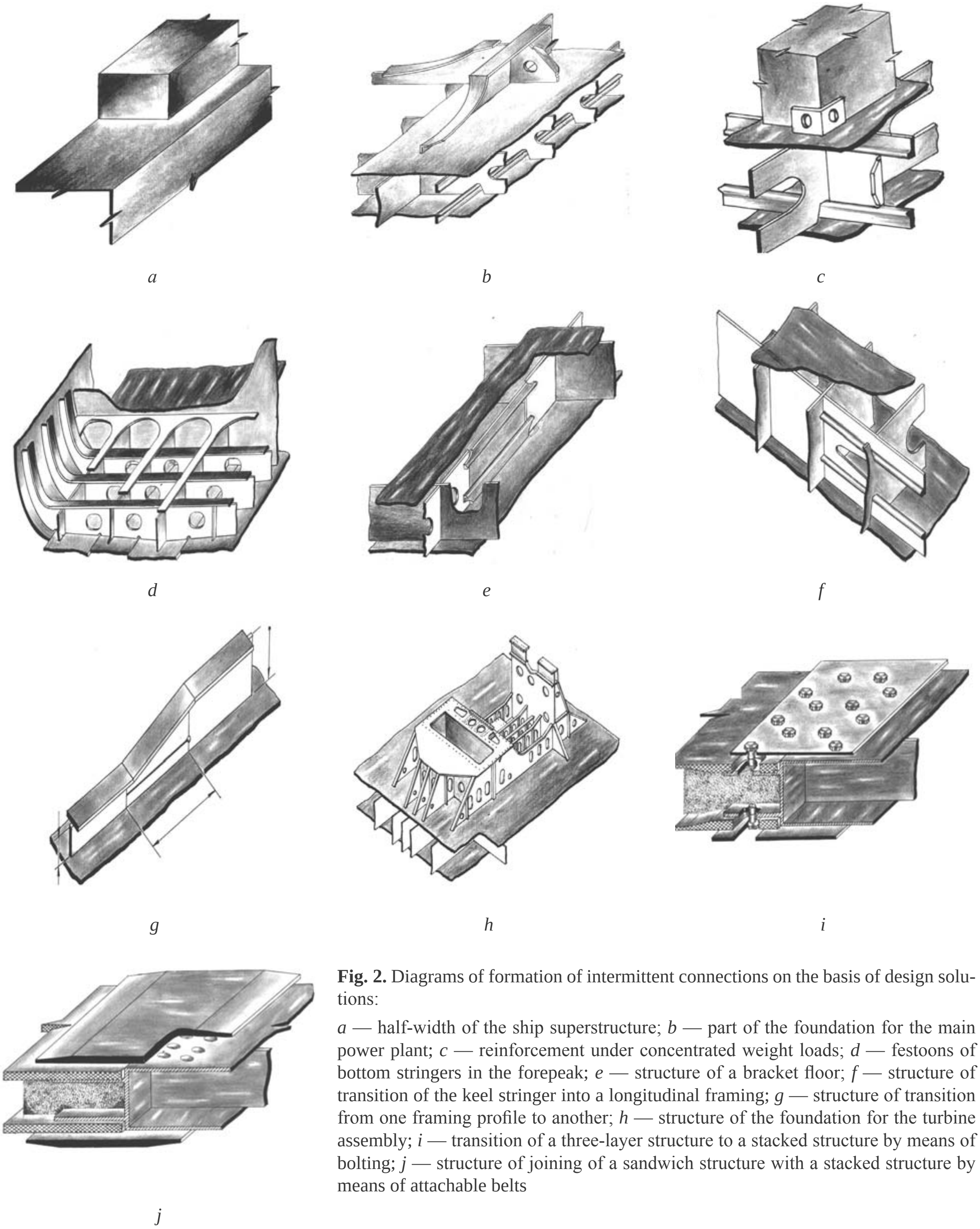


Fig. 2. Diagrams of formation of intermittent connections on the basis of design solutions:

a — half-width of the ship superstructure; *b* — part of the foundation for the main power plant; *c* — reinforcement under concentrated weight loads; *d* — festoons of bottom stringers in the forepeak; *e* — structure of a bracket floor; *f* — structure of transition of the keel stringer into a longitudinal framing; *g* — structure of transition from one framing profile to another; *h* — structure of the foundation for the turbine assembly; *i* — transition of a three-layer structure to a stacked structure by means of bolting; *j* — structure of joining of a sandwich structure with a stacked structure by means of attachable belts

With the purpose of analyzing the stress-strain state of the structure, it is feasible to consider a simple structure in which one of the connections ends abruptly. This problem is considered in papers [2; 4] for the plate exposed to stretching. The aim of these studies is to determine the rigidity coefficient of intermittent connections. It is presented as a ratio of the shear force intensity q_x to the shear displacement u_q of the discontinuous part of a relatively continuous structure. This definition is expressed in [2] as follows:

$$k_r = q_x / u_q, \tag{1}$$

where the shear displacement is of the following form:

$$u_q = \int_0^{\beta \frac{h}{2}} \frac{\tau_{xy}}{G} \cdot dy, \tag{2}$$

Here τ_{xy} is the shear stresses in the cross section of the continuous part deduced from the equilibrium condition at the plane stress state:

$$\tau_{xy} = -\int_0^y \frac{\partial \sigma_x}{\partial x} \cdot dy + (\tau_{xy})_0, \tag{3}$$

Paper [2] assumes that in the cross sections of the discontinuous area that is remote from the end cross sections, normal stresses hardly depend on the y coordinate of the cross section in the discontinuous part. The shear force intensity along the line of attachment of the discontinuous part to the continuous one is equal to

$$q_x = \frac{\tau_{xy} \cdot t}{(1 - \frac{y}{h})}. \tag{4}$$

Equations (2) and (3) include the following quantities: *t* is the thickness of the discontinuous part of the plate, *h* is its width (height), *y* is the coordinate of the cross section in the discontinuous part, $(\tau_{xy})_0$ is the shear stress on the bottom edge of the discontinuous part with the thickness *t*, $\beta \cdot (h/2)$ is the distance of the mean displacement point from the line of attachment to the continuous part of the structure, β is the parameter.

The β parameter is given such a value that the longitudinal force perceived by the discontinuous part and determined according to the approximate theory is equal in magnitude to the force value established through finding an exact solution of the plane problem of the elasticity theory.

The complexity of calculation of the specified parameter β resides in the fact that the plane problem of elasticity theory does not have an exact solution for all intermittent ship structures. Thus, determination of the rigidity coefficient of the discontinuous part requires finding the point of its cross section, the longitudinal displacement of which is equal to its mean displacement during uniform stretching of the discontinuous part. It is the difference in displacement of this point and the point of application of the shear forces (in the same cross section) that defines the shear displacement of the discontinuous part. Expression (4) is based on the approximate theory of intermittent connections. It makes an allowance that in the cross sections of the discontinuous part sufficiently distant from its end cross sections, normal stresses hardly depend on changes in the vertical coordinate y (see [2]).

A somewhat different interpretation of the rigidity coefficient is given in paper [7]. It also defines the rigidity coefficient as the coefficient of proportionality between the shear force q_x and the shift λ_x. By the shift we mean the displacement of the center of gravity of the discontinuous part relative to the center of gravity of the continuous part. Such a shift is made up of three components τ and the shift in the connection between them λ_3. Then we have

$$\lambda_i = \lambda_1 + \lambda_2 + \lambda_3. \tag{5}$$

Accordingly, each term in expression (4) is calculated as follows:

$$\lambda_1 = q/k_1; \quad \lambda_2 = q/k_2; \quad \lambda_3 = q/k_3.$$

In accordance with [7], when a weld joint is used to connect the discontinuous and continuous parts, the coefficient should be taken equal to infinity, and the shift value λ_3 becomes equal to zero.

For the rigidly coefficient of the continuous part k_1 [7], the following expression is adopted:

$$k_1 = \frac{q_x}{\lambda_1} = \frac{q_x}{\int_0^{e_n} \frac{\tau_{xy}}{G} dy}, \tag{6}$$

where *G* is the shear modulus, e_n is the distance between the center of gravity of the discontinuous part and its bottom edge, τ_{xy} is the shear stresses in the cross sections of the discontinuous part depending on the distance from the bottom edge to the discontinuous part.

The dependence of the parameter β on the relative height of the discontinuous part is shown in Fig. 3. Since the upper limits of integration in expressions (2) and (6) are the same, the product of this parameter by the half-height of the discontinuous part $\beta \cdot (h/2)$ actually indicates the distance of the center of gravity of the discontinuous part to its bottom edge e_n.

The values of $\beta \cdot (h/2)$ and en were compared for an intermittent plate with the length of the discontinuous part $l = 2.0$ m, its height being $h = 0.4$ m, with the junction between the discontinuous and the continuous part along an arc of a circle with the radius *R* that is equal to the height *h*. The results of the comparison show that the discrepancy between the specified values does not

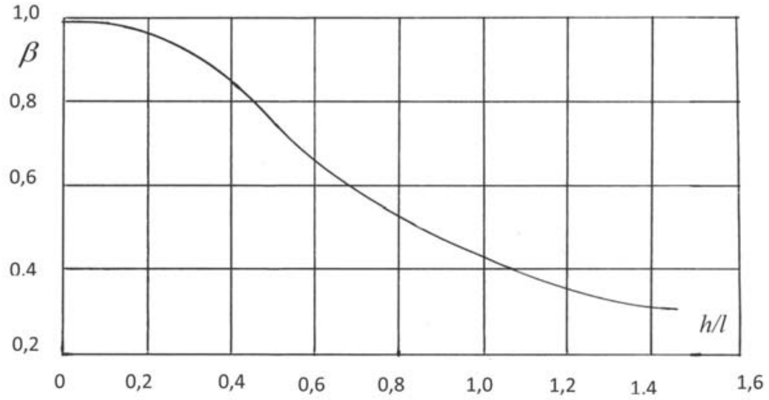


Fig. 3. Dependency of the coefficient β on the relative height of the intermittent connection *h*/*l*, according to [6]

exceed 1.5 %. Hence, the distance of the mean displacement point from line of junction to the discontinuous part of the structure can be used instead of the distance from the center of gravity of the discontinuous part to its bottom edge. Analyzing the diagrams of the formation of intermittent connections shown in Fig. 1 and 2, we can conclude that it is very difficult to determine the value of $\beta \cdot (h/2)$ or e_n for most of them.

Using the numerical methods for assessing the stress-strain state of a structure, it is much simpler to plot a diagram of the shear stress distribution along the line of junction of the discontinuous and continuous parts of the structure. With the help of these stresses, one can calculate the deformations and, ultimately, the rigidity coefficient of the structure under consideration.

As an example, the coefficient of rigidity was determined for a plate schematically shown in Fig. 4, *a*. The boundary element (fictitious load) method was used to establish the shear stresses in the intermittent connection and assess the stress-strain state of the entire structure. The plate was subject to stretching. Fig. 4, *b* presents the diagrams of sheer stresses arising in this case at different levels of the discontinuous part of the plate. At the end, the shear stress distribution is approximated with linear dependencies (Fig. 4, *c*), as suggested in [3].

By analyzing the pattern of the formation of intermittent connections shown in Fig. 1 and 2, one can conclude that some of them are symmetric, while some lack symmetry. In the intermittent connections with no symmetry, simple stretching leads to flexural deformation. This fact complicates estimation of the rigidity coefficient, efficiency of the structure, and concentration of stresses.

The potential opportunity to approximate the shear stress distribution along the junction line between the continuous and discontinuous parts of any structure can significantly simplify determination of its rigidity coefficients.

It follows from Fig. 4, *b* that sheer stresses decrease systematically as the cross sections approach the free edge of the discontinuous part of the plate. The peak of sheer stresses is observed on the arc of coupling of the discontinuous and continuous parts of the plate at the point of intersection of the radius originating from the vertical at the angle of 30°.

Determination of sheer stresses, such as that shown in Fig. 4, *a*–*c*, can be easily realized by means of numerical methods, including the boundary element method. The structures of intermittent connections can be rather diverse. Therefore, there arises the problem of determining the rigidity coefficients of intermittent connections of various designs using the possibility of computation of the sheer stresses at the junction line between the discontinuous and continuous parts of a ship structure. For example, the results shown in Fig. 4, *c* should be analyzed and compared with the data proposed in [3].

The algorithm for calculating the rigidity coefficient of the discontinuous structure shown in Fig. 4, *a* can have the following form.

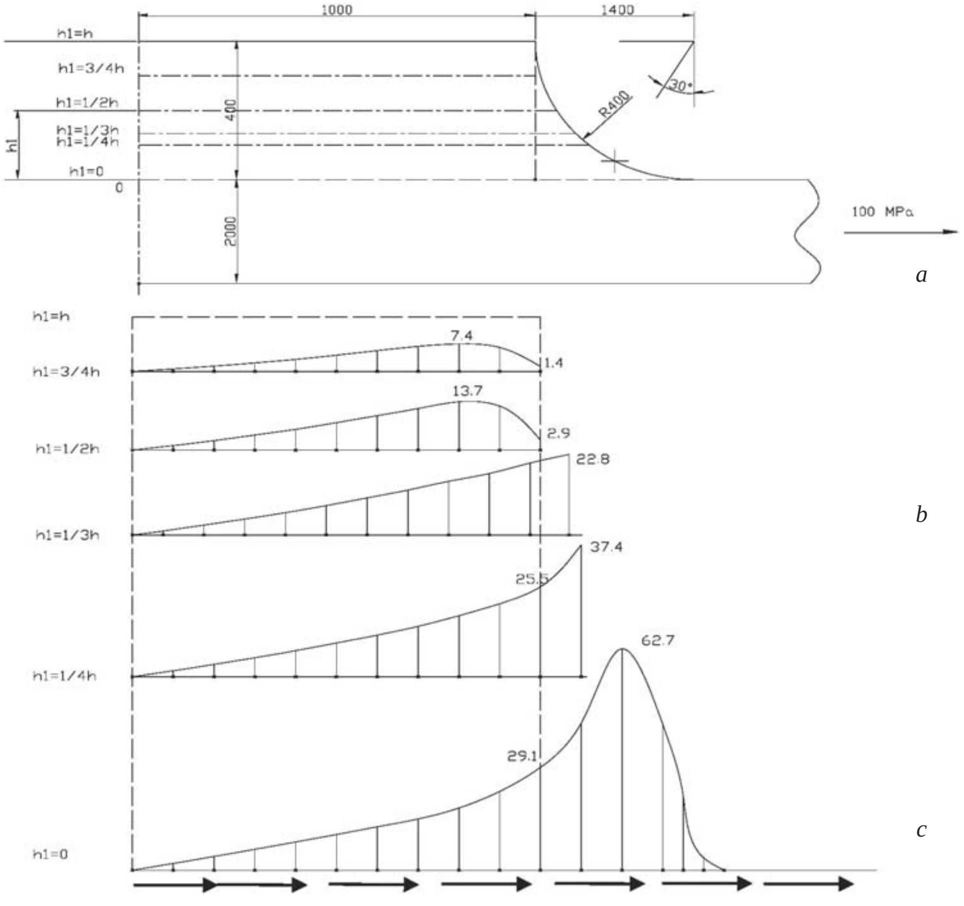


Fig. 4. Diagram of stretching of a discontinuous plate and distribution of sheer stresses along the height of the discontinuous part

1. Split the junction line between the contiguous and discontinuous parts of the plate into equal sections with the interval Δx.

2. Using the data on the acting sheer stresses τij and τjk, calculate the intensity of the acting load:

$$q_{ij} = (\tau_{ij} + \tau_{jk})\Delta x/2, \tag{7}$$

where *i*, *j* and *k* are the boundaries of individual sections.

3. For each section, determine the deformations u_{qij}:

$$u_{qij} = t_i \tau_{ij}/2G, \tag{8}$$

where t_i is the plate thickness, and *G* is the transverse modulus of elasticity, which is calculated as follows:

$$G = E/(2(1+\mu));$$

for steel, $G = 7.69 \cdot 10^4$ MPa.

4. Calculation of the rigidity coefficient kr for each interval:

$$k_r = q_{ijcp}/u_{qij}; \tag{9}$$

where q_{ijcp} is the averaged intensity of the load in the interval.

Based on the results of calculation of the sheer stresses τ_{ij} shown in Fig. 4, *c*, the rigidity coefficient of the discontinuous plate (Fig. 4, *a*) was calculated according to the formulas (7) to (9). As a result of computational procedures, it was established that k_r is equal to 15384 MPa. It is expedient to compare the results of calculations with the dependencies proposed by other authors with the example of the same plate shown in Fig. 4, *a*.

Publication [6] offers the following dependency to determine the rigidity coefficient:

$$k_r = \frac{G\,t_1}{e_2\left(1 - \frac{t_1\,e_2}{2\,f_1}\right)}, \tag{10}$$

where e_2 is the distance of the center of gravity of the cross section of the discontinuous part to its bottom edge, f_1 is the total cross sectional area of the discontinuous part, $f_1 = t_1 h$.

Hence, for an intermittent connection (see Fig. 4, *a*), $t_1 = 0.01$ m, while e_2 is calculated with the help of the following expression:

$$e_2 = \frac{\left(\frac{5}{3} - \frac{\pi}{2}\right)R^2 + \frac{1}{2}\,l\,R}{l + R\left(2 - \frac{\pi}{2}\right)}, \tag{11}$$

A somewhat different representation of the rigidity coefficient is given in [2, 3]:

$$k_r = \frac{G\,t_1}{\beta\frac{h}{2}\left(1 - \frac{\beta}{4}\right)}, \tag{12}$$

where β is the parameter determined according to Fig. 3, depending on the ratio *h*/*l*; at *h*/*l* = 0.2 it makes up 0.97; *h* is the height of the discontinuous part of the connection, *l* = 2 m is its total length.

In accordance with (12), the rigidity coefficient k_r is equal to 5232.7 MPa.

In paper [7], the expression for the rigidity coefficient is virtually the same as in (10):

$$k_r = \frac{2\,G\,t_1}{e_2\left(1 - \frac{t_1\,e_2}{f_1}\right)}. \tag{13}$$

Summing up the results of the calculations with the dependencies (10), (12) and (13), k_r is equal to 7705.4 MPa according to (10), 5232.7 MPa according to (12); and 7705.4 MPa according to (13). The same dependence is described in [4], resulting in the k_r value of 5232.7 MPa.

The same applies to the expressions presented in paper [3], where k_r = 5232.7 MPa. The difference between them varies from 32.1 % to 47.25 %, which calls for refinement and analysis, since the coefficients listed were determined with the help of approximate formulas. When calculating the rigidity coefficients, it appears expedient to be able to determine both shear stresses and strains at the junction between the discontinuous and continuous parts of the structure, which would allow obtaining the required coefficients.

CONCLUSIONS. The patterns of occurrence of intermittent connections as part of a ship structure were systematized. There are basically two such patterns: of intermittent connections based on splitting of the structures with cutouts and formation of intermittent connections on the basis of design solutions. Analytical determination of many quantities necessary to calculate the rigidity coefficient is quite difficult. In this light, it was proposed to employ the numerical definition of the stress-strain state of discontinuous structures by means of the finite or boundary element methods. In such way, one can proceed to calculate the rigidity coefficients. The algorithm was tested using the example of a stretchable discontinuous plate.

Список литературы

[1] **Коробанов Ю. Н.** Анализ предпосылок использования методов граничных элементов в судостроительных системах автоматизированного проектирования [Текст] / Ю. Н Коробанов, О. М. Лищук, И. М. Лищук // Збірник наукових праць НУК. — Миколаїв: Видавництво НУК, 2006. — № 2 (407). — С. 31–38.

[2] **Короткин Я. И.** Прочность корабля. [Текст] / Я. И. Короткин, Д. М. Ростовцев, Н.Л. Сиверс. — Л.: Судостроение, 1974. — 432 с.

[3] **Сиверс Н. Л.** Расчет и конструирование судовых надстроек. [Текст] / Н. Л. Сиверс. — Л.: Судостроение, 1966. — 298 с.

[4] **Курдюмов А. А.** Прочность корабля. [Текст] / А. А. Курдюмов. — Л.: Судпромгиз, 1956. — 384 с.

Статтю рекомендує до друку
д-р техн. наук, проф. *Л. І. Коростильов*