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Ultimate strength of composite ships' hull girders in the presence of composite superstructures

Fattaneh Morshedsoluk, Mohammad Reza Khedmati*

Department of Marine Technology, Amirkabir University of Technology, Tehran 15916-34311, Iran

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An extended formulation of the Coupled Beam Theory (CBT) developed by the authors is employed in order to calculate the ultimate strength of composite ships taking into account of the effect of the superstructure. A nonlinear finite element method is applied for solving the equilibrium equations. Behaviour of the stiffened composite panels in tension and compression is modelled by using progressive failure method. Both hull and superstructure of the ship are modelled using beam elements. Connection between beam elements representing hull and superstructure is made using specially developed spring box elements. Accuracy of the extended method is demonstrated using an available experimental result and also the results of finite element analysis. Also, a set of composite ships having different lengths of superstructure is generated and analysed. Efficiency of the composite superstructure in contribution to the ultimate bending strength of the composite ships is finally evaluated.

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1. Introduction

Laminated composites can be used in different structures in the fields of aerospace, marine and civil engineering. These sorts of composites are generally assemblies of some layers of fibrous composite materials, which can be joined together with the aid of adhesives or resins, in order to provide required engineering properties, including in-plane stiffness, bending stiffness, strength, and coefficient of thermal expansion. It should be emphasised that different structural arrangements of laminated composites including single-skin, stiffened skin and sandwich panels are used in the engineering structures. Application of such materials in ship structures dates back to the late 1970s. Initially, small boats and ships' topsides were being built of such composite materials. Over the time, usage of the composite materials in ship construction continued to grow and in recent years, some longer vessels like frigates and passenger ships are made of laminated composite materials.

Having larger composite ships in length necessitates assessment of their ultimate bending strength in the early stages of structural design. In most of the steel ships, there is no superstructure in the amidships region and thus, the effect of superstructure on the ultimate strength of the ship is negligible. However, composite superstructures are often fitted in the amidships of the composite ships. This leads to the significant contribution of the composite superstructure in the bending strength of the composite ship.

The ultimate strength of steel ships has been widely investigated by many researchers around the world. Caldwell [1] was the first who estimated the ultimate strength of steel ships employing the fully plastic bending theory of the beams. However, he did not consider the reduction in the load-carrying capacity of structural members after they attain their corresponding ultimate strengths. Smith [2] proposed an approach for calculation of the ultimate strength of the ships. He first divided the ship's cross section into different unstiffened/stiffened plate panels, and then performed a progressive collapse analysis under bending on it assuming that the cross section remains plane after bending and each of the panels behaves according to its corresponding average stress–average strain relationship. Finite element method was applied by Smith [2] in order to obtain the average stress–average strain relationships for unstiffened/stiffened panels. Other researchers made some attempts for derivation of the average stress-average strain relationships for ships' unstiffened /stiffened plate panels subject to in-plane compression alone or in combination with other loads using analytical approaches. Among them, reference may be made to the work of Khedmati [3].

In all of above-mentioned research studies, the ultimate strength of the ships is calculated by ignoring the effect of the superstructure. On the other hand, the available theoretical methods to estimate the ultimate strength of the ship's hull with a superstructure are mostly based on the simple beam theory or two-beam theory. Mackney and Rose [4] have studied the effect of the superstructure on the longitudinal strength of a ship both

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* Corresponding author.
E-mail address: khedmati@aut.ac.ir (M.R. Khedmati).

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Nomenclature

A_i	Cross-sectional area of the *i*-th beam
A	Constant Matrix
B	Diagonal matrix containing the singular values
B	Constant Matrix
C_{ij}	Bending moment lever on the *i*-th beam due to the shearing force between the *i*-th and *j*-th beams $=\begin{cases} d_{ij} & j>i \\ 0 & j=i \\ -e_{ij} & j<i \end{cases}$
d_{ik}	Distance between the upper fibre of the beam to the reference line
D	Constant Matrix
e_{ij}	Distance between the lower fibre of the beam to the reference line
E_i^t	Tangential modulus of the *i*-th panel or slope of the mean stress-mean strain curve of the *i*-th panel
EA_i	Axial stiffness of the *i*-th beam
EA_i^t	Tangent axial stiffness$=\sum E_i^t A_i$
EA_i^j	EA value for *j*-th node of *i*-th beam
EI_i	Bending stiffness of *i*-th beam
EI_i^t	Tangent bending stiffness$=\sum E_i^t A_i z_i^2$
EI_i^j	EA value for *j*-th node of *i*-th beam
EX_i	Value which modifies the internal forces if the reference line differs from the centroid of the cross-section
EX_i^t	Tangent modifier of the forces$=\sum E_i^t A_i z_i$
EX_i^j	EX value for *j*-th node of *i*-th beam
H_i	Effective Height of the *i*-th beam
I_i	Sectional moment of inertia of the *i*-th beam
k_{mj}^i	Stiffness matrix elements of *i*-th beam
k_{EAi}	Constant
k_{EIi}	Constant
k_{EXi}	Constant
K	Global stiffness matrix of system
$k_{ij}(x)$	Vertical stiffness between the *i*-th and *j*-th beams
L	Length of hull
L_s	Length of superstructure
M_i	Bending moment of the *i*-th beam
M_x	Ultimate bending strength of the ship under consideration
M_{100}	Ultimate bending strength of the ship with a superstructure of 100 percent efficiency
M_0	Ultimate bending strength of the ship without any superstructure
N_i	Axial force of the *i*-th beam
$N_i[x]$	Shape functions
p_{ij}	Transverse (vertical) distributed forces between the *i*-th and *j*-th beams
Q_i	Shear force of the *i*-th beam
q_i	External force of the *i*-th beam
R_1	Residual
R_2	Residual
s_{ij}	Longitudinal distributed shear forces between the *i*-th and *j*-th beams
R_{12}	Shear strength in plane 12
T_{ij}	Shear stiffness between the *i*-th and *j*-th beams
U	Square and orthogonal matrix
u_i	Axial displacement of the *i*-th beam
u_i^*	Approximate axial displacement of the *i*-th beam
u_j^i	Normal degree of freedom of *j*-th node from *i*-th beam
V	Square and orthogonal matrix
v_i^M	Transverse displacement of the *i*-th beam due to the bending
v_i	Total transverse displacement for the *i*-th beam
v_i^{M*}	Approximate transverse displacement of the *i*-th beam due to the bending
v_j^i	Vertical degree of freedom of j-th node from i-th beam
X_i	First sectional moment of area of the *i*-th beam
X_T	Tension strength in direction 1
X_C	Compression strength in direction 1
Y_T	Tension strength in direction 2
Y_C	Compression strength in direction 2
X_S	Nodal displacement vector of system
z_i	Distance of the *i*-th panel to the reference line
δ_{ij}^u	Relative axial displacement
δ_{ij}^v	Relative transverse displacement
γ_s	Coefficient of efficiency of the superstructure or superstructure effectiveness coefficient
σ_1	Normal stress in direction 1
σ_2	Normal stress in direction 2
τ_{12}	Shear stress in plane 12
θ_j^i	Tangential degree of freedom of j-th node from i-th beam

experimentally and numerically. The simple beam theory and finite element method were applied in their study, while they ignored the effect of the connection between the hull and superstructure. Naar et al. [5] proposed a new approach called Coupled Beams Method (CBM) to evaluate hull girder response of passenger ships. This method is based on the assumption that the global bending response of a modern passenger ship can be estimated with the help of beams coupled to each other by distributed longitudinal and vertical springs. To solve the governed equations, Naar et al. [5] proposed an analytical method that was only applicable when the superstructure is as long as the ship's hull.

Very few publications can be found in the literature addressing the issue of ultimate strength of composite ships. Chen et al. [6] were the first who tried to estimate the ultimate strength of composite ships. They proposed a simple analytical method for calculating the ultimate strength of composite vessels. In their method, the behaviour of composite panels was formulated with a simple formula. Chen and Soares [7] extended the above-mentioned method for calculating the ultimate strength of composite ships under bending moment. Two types of the failure modes were considered in their study; the panel buckling as well as fracture of the composite materials. Later, Chen and Soares [8] estimated the reliability of composite ships under bending moment, using the first method proposed by Chen et al. [6]. To calculate the reliability of the reinforced plate buckling failure, the failure of the first layer of the reinforcing plate and the ultimate failure of the reinforced plate were considered. Finally, Chen and Soares [9] used Smith's method, which is a conventional approach and capable of calculating bending moment-curvature curves, in order to calculate the ultimate strength of composite vessels.

Application of the composite materials to the construction of long ships is still a relatively new and growing subject, which needs more research to be performed on assessment of the ultimate strength of these types of the ships. Besides, most of the previous studies do not take into account of the effect of the superstructure on the ultimate strength of the ships.

As it is understood from the above-mentioned review, ultimate strength of the ships taking the superstructure's effect into account have been studied in many aspects, the most of which are only devoted to the linear elastic material behaviours.

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