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Ultimate strength of steel brackets in ship structures

Sang Eui Lee [a], Anil Kumar Thayamballi [a], Jeom Kee Paik [a,b,]*

[a] The Korea Ship and Offshore Research Institute (The Lloyd's Register Foundation Research Centre of Excellence), Pusan National University, Busan 609-735, Republic of Korea
[b] Department of Mechanical Engineering, University College London, Torrington Place, London WC1E 7JE, UK

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ABSTRACT

Steel brackets are customarily used to prevent sideways deformation or lateral-torsional buckling in the supporting components of structures such as ships and offshore platforms. The aims of this study are to undertake nonlinear finite element analysis to examine the ultimate-strength characteristics of steel brackets, and to develop a simple design formula to predict the ultimate strength of a steel bracket. The structural features of steel brackets in real ship structures are investigated. Finite element modelling techniques are developed to compute the ultimate-strength behaviour of steel brackets with different design variables, such as material type and breadth to height ratio. The findings of the research and the above-mentioned design formula have the potential to enhance the structural design and safety assessment of steel brackets in ship structures.

1. Introduction

Steel-plated structures are widely used in structural systems such as ships and offshore platforms. They are composed of plate panels supported by beam members such as longitudinal girders, transverse frames and stiffeners. As these supporting members tend to deform sideways, brackets are attached to prevent lateral-torsional buckling or ‘tripping’ (Paik and Thayamballi, 2003; Hughes and Paik, 2013).

The regulations established by various classification societies (DNVGL, 2012; IACS, 2006a, 2006b; LR, 2012) can be used to determine the scantling requirements for steel brackets at the structural-design stage. However, no detailed guidelines for predicting the strength performance of steel brackets are available.

It is noted that research efforts to investigate the strength of a steel bracket which has a triangular shape are relatively far less than rectangular plates such as plates and stiffened panels (Paik and Thayamballi, 2003; Vhanmane and Bhattacharya, 2008; Zhang et al., 2008; Paik and Seo, 2009a, 2009b; Shi and Wang, 2012; Paik et al., 2012). For over the last century, there were a number of researches related to buckling analysis of a equilateral triangular plate (Woinowsky-Krieger, 1933; Conway and Leissa, 1960; Wakasugi, 1960b, 1961) and a isosceles triangular plate (Burchard, 1937; Wittrick, 1954; Li, 1959; Cox and Klein, 1955; Han, 1960; Wakasugi, 1960a; Salmon, 1962; Salmon et al., 1964; Ueda et al., 1976, 1977; Tan et al., 1983; Krishnakumar, 1988; Wang and Liew, 1994; Vaaraniemi et al., 2003; Safar and Machaly, 2005; Aung, 2006) under compressive, shear force or combination of them.

In the early days, the buckling analysis of triangular plates analytically involved. In particular, Salmon (1962) studied the elastic stability characteristics of the connection utilising the Rayleigh–Ritz method under the assumption that the load is linearly applied on the loaded edge of the bracket with no horizontal displacement. Further, Salmon et al. (1964) conducted a series of laboratory tests to investigate the behaviour of eighteen connections with aspect ratio ranging from 0.75 to 2.0 for small and large plate dimensions to include plates where buckling and yielding are anticipated. It was confirmed that the maximum compressive stress takes place at the free edge which is found on his previous analytical work (Salmon, 1962). Wang and Liew (1994) utilised the *pb*-2 Rayleigh–Ritz method to investigate the triangular plates under isotropic in-plane compressive load. Further the study was extended to buckling of triangular thick plates based on the Mindlin plate theory (Xiang et al., 1994; Wang et al., 1994). Jaunky et al. (1995) studied the buckling of general triangular anisotropic plates subjected to combined in-plane loads utilising the Rayleigh–Ritz method. Xiang (2002) further investigated the buckling behaviour of triangular plates with both translational and rotational elastic edge constraints using the *p*-Ritz and presented extensive buckling factors for several selected isosceles and right-angled triangular plates at various edge boundary conditions under isotropic in-plane compressive load. Aung (2006) also used Mindlin plate theory to investigate the elastic–plastic buckling of various isosceles and right-angled triangular plates under combined compression and shear force.

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* Corresponding author at: The Korea Ship and Offshore Research Institute (The Lloyd's Register Foundation Research Centre of Excellence), Pusan National University, Busan 609-735, Republic of Korea. Tel.: +82 51 510 2429; fax: +82 51 518 7687.
E-mail address: jeompaik@pusan.ac.kr (J.K. Paik).

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Nomenclature

b_1	Breadth of the steel bracket
b_2	Breadth of steel-bracket toe
E	Elastic modulus of material
g	Increment factor of ultimate bending moment
f_{yi}	Force component on the y-axis at the i-th node
h_1	Height of the steel bracket
h_2	Height of the steel bracket toe
M_P	Plastic bending moment of the steel bracket
M_u	Ultimate bending moment of the steel bracket
$(M_u/M_P)_F$	Nondimensionalised ultimate bending moment with fixed boundary condition
$(M_u/M_P)_S$	Nondimensionalised ultimate bending moment with simply supported boundary condition
$(M_u)_{Triangular}$	Ultimate bending moment of the triangular steel bracket
$(M_u)_{Radius}$	Ultimate bending moment of the radiused steel bracket
R	Radius of the steel bracket
R_x	Rotational loading on the vertical edge of the steel bracket
R_u	Reduction factor of ultimate bending moment
s	Reduced area of the steel bracket with the radius at the free edge
S	Area of the triangular steel bracket
t_b	Thickness of the steel bracket
u_x	Displacement on the x-axis
u_y	Displacement on the y-axis
u_z	Displacement on the z-axis
w	Reduced area ratio
w_o	Initial imperfection of the steel bracket on the x-axis
y'	y-axis along with the diagonal line c-c
z_i	Vertical distance from the origin to the i-th node
Z_P	Plastic section modulus of the steel bracket
α	Aspect ratio of steel bracket
β_1	Slenderness ratio (height to thickness) of the steel bracket
β_2	Slenderness ratio (breadth to thickness) of the steel bracket
γ_i, η_i, κ_i	Coefficients of design formula for a simply supported boundary condition
θ_x	Rotational restraints on the x-axis
θ_y	Rotational restraints on the y-axis
θ_z	Rotational restraints on the z-axis
λ_1	Radius ratio (radius to height) of the steel bracket
λ_2	Radius ratio (radius to breadth) of the steel bracket
μ_i	Coefficient of design formula for a fixed boundary condition
ν	Poisson's ratio
σ_x	Axial compressive load on the x-axis
σ_Y	Yield stress of the material
$\sigma_{z'}$	Stress component on the z-axis perpendicular to the diagonal line c-c
ς_i, ξ_i, ψ_i, ζ_i	Coefficients of design formula for a fixed boundary condition

As computing speeds and capabilities of numerical tools advance, it is expected that numerical simulations will play an important role and contribute to accelerate the level of researches higher than before. Particularly, the numerical simulations to examine the buckling analysis of triangular plates have been employed by lots of researchers (Ueda et al., 1976, 1977; Tan et al., 1983; Vaaraniemi et al., 2003; Safar and Machaly, 2005).

The most distinguished numerical and experimental works are Ueda's series of studies (Ueda et al., 1976, 1977; Ueda and Yao, 1987) for the triangular corner brackets using finite element method (FEM). A series of buckling analysis, elastic–plastic large deflection analysis and elastic–plastic thermal stress analysis were conducted for the triangular corner brackets subjected to compression to clarify the effects of initial imperfection due to welding (Ueda et al., 1977). It was observed that initial deflection decreases the rigidity and ultimate strength of a triangular corner bracket and this tendency is more remarkable when the side length to thickness ratio decreases. It was found that the welding residual stresses in the triangular corner bracket are usually in tension, and these stresses increase the buckling strength and the ultimate strength of the bracket. At last, a method was proposed to determine the optimum thickness of a corner bracket in relation to buckling and/or plastic strength (Ueda and Yao, 1987). The fundamental idea of the proposed method was that the collapse of a frame and a bracket takes place at the same time, since it is of no use for a bracket to carry more loads after the frame has collapse. However, in case of brackets attached to prevent lateral-torsional buckling or ‘tripping’ of stiffeners, it is not always true. If a bracket carries more loads, a stiffened-plate panel would stand more.

Furthermore, Safar and Machaly (2005) conducted experimental and analytical research work on triangular bracket plates considering both material and geometric nonlinearities. It was experimentally confirmed that yielding along the free edge usually takes place prior to buckling and the distribution of contact stresses between the beam and the bracket was triangular in shape with the peak stresses at free edge of bracket at buckling. It was concluded that the connection possesses a significant amount of post-buckling strength such that the limit load is almost twice the critical load. The results of all studies offer useful insights into the design of steel brackets. To the best of the authors' knowledge, however, a limited number of researches have been conducted on either the load-carrying capacity of brackets or their ultimate strength.

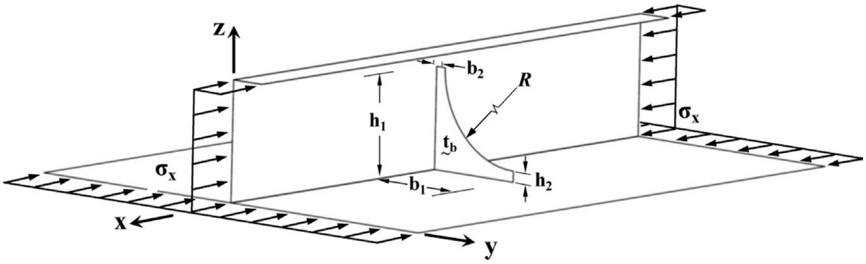

Fig. 1. A schematic representation of typical steel bracket attached to a strong support member.