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A benchmark analytical approach for evaluating ultimate compressive strength of hollow corrugated stub columns

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ABSTRACT

This paper deals with developing advanced, yet design-oriented expressions for ultimate strength of the newly developed hollow corrugated stub columns with or without ultra-high strength corner tubes under uniaxial compressive loading. This is achieved by individually analysing comprising self-strengthened corrugated plates using the effective width concept whilst the effect of corner enhancement is taken into calculation. For stiffened panels such as corrugated plates, the ultimate limit state design is equated to the lowest value among all collapse provisions. However, the finite element analyses show that Euler buckling state may govern the ultimate load capacity of corrugated plates used in the proposed columns. This is verified by comparing the results obtained from the proposed analytical formulations with those demonstrated by the finite element modelling and experiments. The results are also compared with the guidelines for design of corrugated panels available in the literature. Finally, several cases with different corrugation geometrical parameters are defined and the capacity of corresponding columns is evaluated and compared to each other.

1. Introduction

Innovative corrugated sections comprised from relatively thick corrugated plates have a strong potential to open a new horizon in infrastructure. Not only have corrugated plates shown their performance as a part of corrugated web I-girders [1–3], but their superior mechanical performance in corrugated stub columns has also been investigated compared to conventional tubular columns [4,5].

Luo and Edlund [6] studied the buckling of trapezoidally corrugated plates under in-plane loading. The influence of various parameters, such as geometry, loading forms and boundary conditions, etc. on the elastic buckling load was also investigated. Gao et al. [7] studied seismic capacity of thin-walled corrugated concrete-filled steel tube column. They concluded that the dissipation energy capacity of new style columns is better than that of square and circle under the same displacement conditions.

It has been shown that corrugated plates are capable to be utilised in variety of configurations as part of infrastructure elements [4,5,8]. Also, by replacing conventional welded sections with corrugated box sections, environment-friendly and resilient infrastructure can be achieved. The more resilient structures, the higher performance of structures under extreme actions is expected [9–15]. Although there is lack of appropriate design formulations for the corrugated stub columns in the current building codes of practice, few provisional methods [16–18] and also direct strength method [19] have been proposed which could be used for evaluating restricted ranges of corrugated panels in offshore structures. According to the Australian standards [20], the ultimate strength of fabricated hollow steel columns is evaluated based on the buckling and limit state analysis of comprising elements. Whether or not a similar approach can be undertaken for the fabricated hollow columns made of corrugated plates, it needs to be thoroughly investigated.

The corrugated plates are regularly produced in different forms of profiles by folding the original flat plates. The corrugation increases the bending strength of the plate in the direction perpendicular to the corrugations [5]. Researchers have used the classic theory of orthotropic shells to adequately predict the key mechanical properties of corrugated shells. Briassoulis [21] investigated trapezoidal corrugated sheets by considering the equivalent orthotropic plates. This study was only carried out based on equating flexural rigidities; however, some other researchers developed analytical expressions for a corrugated sheet by also considering both extensional and flexural rigidities [22,23]. Samanta and Mukhopadhyay [24] investigated the geometric nonlinear analysis of folded plate by treating it as an equivalent orthotropic model for the first time. Wennberg et al. [25] compared different analytical expressions for the mechanical properties of corrugated sheets using the 3D finite element calculations under extension, free vibration, and buckling state. By this comparison, they concluded

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Nomenclature

a	Length of top-horizontal segment in a corrugation module
b	Length of bottom-horizontal segment in a corrugation module
c	Length of inclined segment in a corrugation module
d	Horizontal projection length of inclined segment in a corrugation module
h	Corrugation height
i	Any of a, b, or c lengths
k	Local buckling coefficient
k_{mn}	Orthotropic plate's buckling coefficient
m	Number of half-sine waves in longitudinal direction
n	Number of half-sine waves in lateral direction
q	Unfolded width of a corrugation module
q_x	Uniform distributed in-plane compressive load
q_{cr}	Critical distributed buckling load
q_{mn}	Uniform distributed load creating m and n half-sine waves in a plate
r	Radius of gyration
s	Horizontal projection width of a corrugation module
t	Corrugated plate thickness
t_x	Equivalent thickness of the corrugation in the corrugation direction
u, v, w	Longitudinal, transverse and out of plane displacement components, respectively
w_{eff}	Effective width
x, y, z	Cartesian coordinates in longitudinal, transverse and out of plane directions
A	Cross section area
A_{mn}	Arbitrary constant for m and n half-sine waves
B	Overall corrugated plate width
E	Young's modulus
F_u	Ultimate load capacity of corrugated stub column
$F_{u,H}$	Ultimate load capacity of hybrid stub column
$F_{u,UHS}$	Squash load of single UHS tube
$F_{seg,i}$	Load carrying capacity by the segment i
I	Second moment of area for a strut
$I_{u,yy}$	Second moment of area along y-axis for a corrugation module
I_{yy}	Second moment of area along y-axis for a corrugated plate
L	Overall corrugated plate length
N	Strut's buckling mode shape number
N_u	Number of corrugation modules in a plate
N_x	Internal force acting in the middle surface of the plate in x direction due to in-plane loading
P	Compressive load for a strut
P_{cr}	Critical buckling load for a strut
α	Angle of inclination
γ	Ratio of horizontal segments (a/b)
η	Maximum allowable strength utilization factor
λ	Slenderness ratio
λ_1	Maximum theoretical slenderness of a strut compressed to the yield strength
λ_y	Slenderness ratio which generate yield stress distribution
ν	Poisson's ratio
ρ	Corner radius (average of inner and outer radii)
σ_a	Maximum compressive stress in the corrugation direction
σ_{CA}	Unit corrugation critical buckling stress
σ_{cr}	Critical local buckling stress
σ_{cr}^E	Euler's critical buckling stress
$\sigma_{E(C)}$	Elastic buckling stress
σ_x	Average compressive stress in corrugation direction
σ_{lim}	Limiting stress
σ_y	Yield stress
$\sigma_{y,c}$	Enhanced yield stress at corner regions
$\sigma_{y,w}$	Weighted yield stress for each flat strip
$\sigma_{0.2\%}$	0.2% proof stress (offset yield point)
ϕ	Plate aspect ratio
$\mathbf{A}$	Extensional stiffness matrix
$\mathbf{B}$	Flexural-extension coupling matrix
$\mathbf{D}$	Flexural stiffness matrix
$\mathbf{N}$	Force vector
$\mathbf{M}$	Moment vector
$\boldsymbol{\varepsilon}$	Mid-plane strain vector
$\boldsymbol{\kappa}$	Mid-plane curvature vector

with general expressions for flexural and extensional rigidities based on different approaches. Xia et al. [26] suggested a homogenisation-based analytical model which could be used for any corrugation shape. They provided explicit expressions to calculate the equivalent material properties of trapezoidal and round corrugation profiles based on a simplified geometry for a unit-cell and the stiffness properties of original sheet.

Apart from existing applications of corrugated bulkheads in marine structures, an increasing trend of using corrugated panels in construction can be seen. This is due to significant saving in terms of construction time and costs in offshore structures. These elements may serve as watertight bulkheads, or when connected with fasteners, they are employed as corrugated shear diaphragms. Due to industry demand, the American Bureau of Shipping (ABS) has developed design recommendations for the buckling strength assessment of corrugated panels with triangular and trapezoidal profiles [17]. However, the suggested buckling strength criteria are valid for plates with limited range of corrugation angle (i.e. between 57 and 90 degrees). The ABS guide has introduced three provisional collapse modes for the corrugated plates named as local (flange or web) plate buckling, beam-column (unit corrugation) buckling, and overall buckling of entire plate [17]. For each mode of failure, separate analytical equations were derived whilst it was suggested that the failure mechanism starts to form as soon as the axial load value reaches the lowest buckling criterion. Thereafter, Sun and Spencer [18] described the main features and the principles ABS guide used, along with their technical background. Although the limited range presumed in ABS guide might look practical for marine structures, it may not cover the wide range of corrugation angles. On the other hand, there are some geometric limitations in the direct strength design method [19] which similarly disqualify implementing this method in the current study.

Corrugated hollow sections could be fabricated in two forms: four identical corrugated plates welded together or four identical corrugated plates welded to four tubes located at the apexes of a box section. In this paper, the characteristics of the proposed stub columns are briefly explained while more details can be found from the recent publications [4,5]. Note that as per definition, a stub column is a column whose length is sufficiently small to prevent failure as a column, but long enough to contain the same residual stress pattern that exists in the column itself [27]. An analytical approach is then developed to estimate the ultimate load capacity of both forms of corrugated stub columns. This will be achieved by examining individual corrugated plates under uniaxial loading using effective width concept. This technique is demonstrated to be valid through finite element (FE) investigations. In order to certify the developed method, the results are compared with those obtained from FE analysis which has already been validated against the experimental data for corrugated stub columns [4,5]. The results will also be compared to those of alternative approach available in literature [17,18].