Thin-Walled Structures 122 (2018) 416–424

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Ultimate longitudinal compressive strength of steel plates with lateral patch load induced plastic deformation

Burak Can Cerik*,[1]

School of Marine Science and Technology, Newcastle University, Newcastle upon Tyne, UK

ARTICLE INFO

Keywords:
Damaged plate
Residual strength
Ultimate strength
Lateral patch load
Longitudinal compression
Large imperfection

ABSTRACT

The aim of the present study is to investigate the influence of large plastic deformation caused by lateral patch load on longitudinal compression behaviour of steel plates. A series of nonlinear finite element analyses are undertaken with a two-step procedure. Plastic deformation is induced in the first step by applying lateral pressure as a patch on the plate and the plate is subjected to monotonically increasing unixial compression load in the second step up to and beyond collapse. The residual stresses resulting from plastic deformations are retained in the collapse analysis. The plates are also analysed in intact condition. The effects of lateral patch load width and permanent set amplitude, as well as plate slenderness ratio are examined. The results reveal that the damage reduces the pre-collapse stiffness of the plates significantly. In addition, as plastic deformation is more localised, its detrimental effect on plate ultimate strength is more severe.

1. Introduction

For steel-plated structures, the importance of welding-induced initial deformations and residual stresses has been generally well recognised concerning their ultimate limit state design. On the other hand, in-service effects, such as age related degradation (fatigue damage, corrosion) and plastic deformation due to extreme or abnormal loads should also be considered with respect to other three limit states, namely, fatigue, serviceability and accidental limit states. Plastic deformation due to extreme or abnormal loads is closely associated with the effect of imperfections, such that ultimate strength performance of structures in damage condition requires a particular attention. In particular, the load carrying capacity of stiffened panels under in-plane compressive loads depends critically on the load-shortening response of individual rectangular plate elements bounded at their sides by longitudinal stiffeners and transverse frames. Hence, not only the ultimate strength of plate elements in damage condition but also by pre-collapse and post-collapse behaviour require consideration for the sake of structural safety.

In the context of marine structures, which are usually large assemblies of steel plates, large inelastic out-of-plane deformation of platings may be caused by collision [1–3], grounding, dropped objects, hydrodynamic impact [4], explosion/air blast effects [5] or abnormal ice actions (ice pressure overload) [6]. In the plastic design of polar class ship structures, the latter is usually assumed to act on a limited length of the rectangular plate (termed as patch) and the plastic deformation is essentially confined to the plate element with little distortion of the stiffeners [6]. This type of damage may occur also in soft grounding of ships, if the contact area between the seabed and bottom plating of the ship is relatively small. In addition, drop of large grab buckets on double bottom platings of bulk carriers, fall of heavy objects on deck panels of ships, minor (low energy) collisions between floating offshore installations and attending vessels may result in similar localised plastic damage on plate elements. It is important to note that most of these plate elements require withstanding large in-plane compressive loads in longitudinal direction that may result from hull girder bending or topside weight acting on columns of floating offshore installations.

Smith and Dow [7] were first in applying nonlinear finite element analysis (NLFEA) for the analysis of structural response of damaged steel-plated structures. In the literature, there are numerous research works, which utilise NLFEA for this purpose, albeit with some differences in modelling techniques. A common approach is to idealise the shape of the deformation by using appropriate mathematical expressions (usually sinusoidal). As in modelling the welding-induced imperfections for the analysis of intact plates, the distorted geometry of plated structures is modelled by translating the nodal coordinates of the elements. This technique has the advantage of giving the analyst a full control on the damage extents and the shape, and eliminates the need for an explicit simulation of the damage process, i.e. structural impact simulation. However, as one would expect, large inelastic deformations

* Corresponding author.
E-mail address: bccerik@inha.ac.kr.
[1] Present affiliation: Department of Naval Architecture and Ocean Engineering, Inha University, Incheon, Republic of Korea.

http://dx.doi.org/10.1016/j.tws.2017.10.030
Received 28 July 2017; Received in revised form 8 September 2017; Accepted 16 October 2017

Nomenclature

β	plate slenderness ratio
ε_p	plastic strain
ε_Y	yield strain
$\varepsilon_{x,ave}$	average axial compressive strain
ν	Poisson's ratio
σ_0	flow stress
σ_u	ultimate tensile strength
σ_Y	yield strength
$\sigma_{u,x}$	plate ultimate compressive strength
$\sigma_{x,ave}$	average axial compressive stress
$\theta_{x,y,z}$	rotation about x,y,z axis
a	plate length
A_{0i}	Fourier series coefficient
b	plate width
E	Young's modulus
f_B	adjustment factor
K	strain hardening coefficient
K_m	parameter representing membrane effect
K_p	influence factor finite length
M_p	fully plastic bending moment per unit width
n	strain hardening exponent
p	lateral patch load magnitude
s	patch length
t	plate thickness
u	displacement in longitudinal direction
v	displacement in transverse direction
w	displacement in lateral direction
w_0	lateral deflection of plate due to initial imperfection
w_{0pl}	initial imperfection magnitude
x	longitudinal direction
y	transverse direction
z	lateral direction

are associated with residual stresses, which are inevitably ignored if damage is simulated by direct node translation. A quick literature review also reveals that the damage type considered in the relevant research work is much localised, i.e. in form of isolated dents and dimples accompanied with relatively little global plate deformation, or, in contrast to localised damage, full length deformation of the plate is considered, which is referred to as dishing. Lateral patch load induced damage, on the other hand, has virtually not been considered in any of the past studies. A summary of the relevant research work and the new aspects covered in the present study is presented in Table 1.

Against this background, the aim of the present paper is to examine the load-shortening behaviour of rectangular steel plates with patch load induced damage by including a simulation of the damage process in order to account fully for damage effects. Emphasis is given to the full range response of the plates, i.e. pre-collapse, collapse and post-collapse. Some simulation techniques are suggested and the areas, which require further investigation, are identified.

2. Plastic deformation due to lateral patch load

With reference to [6], the collapse mechanism of a rectangular plate with the length a, the width b and the thickness t, subject to lateral patch load, can be illustrated as shown in Fig. 1. The important parameters regarding the load are the patch load length s, and the patch load magnitude, p. By using the upper bound theorem and adopting so-called "double-diamond" mechanism with the yield lines shown in Fig. 1, Hong and Amdahl [6] derived the following pressure–lateral plastic deformation ($p - w$) relationship:

$$p = \frac{16M_p}{b^2}K_pK_mf_B \tag{1}$$

Table 1
Summary of related research and comparison with the present study.

Reference	Structure	Damage	Damage simulation	Residual stress
[7]	Plate	Dishing	Uniform pressure	○
[8]	Plate	Dent	Translation of nodes	×
[9]	Plate	Dent	Translation of nodes	×
[10]	Plate	Dent	Translation of nodes	×
[11]	Plate panel	Dishing	Lateral displacement	○
[12]	Stiffened plate	Dishing	Lateral displacement	○
[13]	Plate panel	Dimple	Translation of nodes	×
[14,15]	Stiffened panel	Dent	Mass impact	○
[16]	Plate panel	Dent	Translation of nodes	×
[17,18]	Single plate	Dent	Translation of nodes	×
This study	Plate	Patch	Patch load	○

In this equation, K_p represents the influence factor of finite length and given by

$$K_p = 1.0 + 1.3(b/s) + 0.18(b/s)^2 \tag{2}$$

K_m is the parameter that represents the membrane effect:

$$K_m = \begin{cases} 1.0 + 1.3(w/t)^2\left[\dfrac{-(b/s)^2 + 9(b/s) - 16 + 36(s/b)}{-(b/s) + 12 + 12(s/b)}\right] & \text{if } w/t \le 1 \\ 2(w/t)\left[1 + \dfrac{(b/s)^2 - 12(b/s) + 52}{-4(b/s) + 48 + 48(s/b)}\left(\dfrac{1}{3(w/t)^2} - 1\right)\right] & \text{if } w/t \ge 1 \end{cases} \tag{3}$$

Finally, f_B is an adjustment factor given by the following expression:

$$f_B = 1 - 0.075(s/b)^{-0.5} \tag{4}$$

The plastic bending moment capacity M_P of a plate strip per unit width is calculated as

$$M_p = \sigma_0 t^2/4 \tag{5}$$

The flow stress, σ_0, may be taken as the average of yield strength, σ_Y, and ultimate tensile strength, σ_u, to allow for the strain-hardening effects.

The above formulation is particularly useful for the present study to determine the required pressure magnitude for a given lateral plastic deformation (permanent set) of a plate. It should be noted that following the rigid-plastic mechanism approach, elastic effects are ignored in this formulation. Hence, the estimation for the required pressure magnitude would be somehow inaccurate, particularly, if significant elastic spring-back is involved after the load removal.

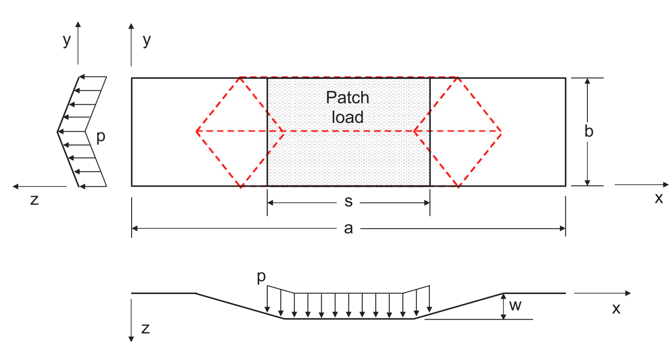

Fig. 1. Laterally patch loaded plate and its collapse mechanism.