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An analytical SCF solution method for joint misalignments and application in fatigue test data interpretation

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A R T I C L E I N F O

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In this study, we first present a general analytical method for calculating stress concentration factors in a cruciform connection containing either axial or angular misalignment between two intercostal members through an application of Castigliano's second theorem. As such, various end restraint conditions of interest in practice can be considered with ease. Such a solution method provides stress concentration factors at intersection location not only with respect to intercostal members, but also with respect to continuous members. A comprehensive set of SCF solutions, confirmed by finite element solutions, are then presented in tabular forms which can be used as supplements to the existing SCF solutions such as those given in BS 7910 and DNV-RP-C203 for performing fatigue and fracture assessment of welded connections. Some of the existing solutions are shown to be valid only under a narrower set of conditions than documented and some seem to be in significant error. As a further demonstration of the validity of the analytical approach presented in this paper, the same analytical formulation is applied for examining interaction effects between misalignments and fatigue testing conditions, resulting in significantly improved correlation of fatigue test data obtained as a part of this study.

1. Introduction

Load-carrying fillet-welded connections are commonly used in welded structures and prone to misalignments either due to poor fit-up conditions prior to welding or distortions developed during welding assembly [1–3]. Two types of misalignments (i.e., axial misalignment and angular misalignment, as illustrated in Fig. 1, respectively) must be controlled to within an acceptable tolerance during manufacturing and structural assembly in order to avoid any significant impact on joint fatigue performance. For ship structures, the acceptable limits may be defined as one half of plate thickness of the discontinuous member (or intercostal member) for axial misalignments and one half of plate thickness at an intercostal plate position based on stiffener spacing, as recently discussed by Huang et al. [4]. Fig. 1 shows two representative fatigue test specimens among those investigated in this study: one exhibits dominantly axial misalignment (see Fig. 1(a)) and the other angular misalignment (see Fig. 1(b)). These misalignments were considered acceptable under typical shipyard environment, for which fatigue test results have been presented in Ref. [5] and analyzed using a new traction stress method.

There have been numerous analytical and experimental studies in the literature on effects of manufacturing-caused misalignments on fatigue performance of welded joints, such as on load-carrying cruciform joints [6–8], butt-seam

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Nomenclature

c_A, c_B	constants associated with dimensions of structural members
$d(x)$	transverse displacement resulted from specimen griping
e	axial misalignment
$e'(x)$	eccentricity after griping
K	stress concentration factor
k_e	axial misalignment-induced SCF
k_α	angular misalignment-induced SCF
$k_{e+\alpha}$	SCF resulted from both axial and angular misalignments
l	structural member length
m	reaction moment due to applied reference load
m_i	moment distribution on *ith*(i=1,2) member of fatigue specimen due to fatigue loading
p	applied reference loading
r	bending ratio
s	fillet weld size
t	thickness of specimen
t_e	effective thickness
t_i	plate thickness of *ith*(i=1,2,3,4) structural member
v	reaction shear force due to fatigue loading
A	cross section areas of test specimen
A_i	cross section areas of *ith*(i=1,2,3,4)structural members
E	Young's modulus
F	dummy force
I	moment of inertia of cross section of test specimen
I_i	moment of inertia of cross section of *ith*(i=1,2,3,4)structural members
$I(r)$	dimensionless life integral as a function of bending ratio r
L	total length of a test specimen
L_c	position of critical location
L_i	length of *ith*(i=1,2,3,4)structural members
M	reaction moment due to gripping
M_i	reaction moments at *ith*(i=*I*,*II*,*III*,*IV*) end positions
M_i	moment distribution on *ith*(i=1,2,3,4) structural member
P_i	reaction forces at *ith*(i=*II*,*III*,*IV*)end positions
P_i	axial force distribution along *ith*(i=1,2,3,4) structural members
U	strain energy
$U_{bending}$	strain energy due to bending
$U_{tensile}$	strain energy due to axial loading
V	reaction in transverse shear due to specimen gripping
V_i	reaction shear forces at *ith* (i=*I*,*II*,*III*,*IV*) end positions
X	axial location of dummy force
α	angular misalignment
σ_b	misalignment induced bending stress
σ_p	applied reference membrane stress
σ_{p1}	membrane stress in structural member 1
κ	dimensionless scaling parameter
$\Delta\sigma_b$	bending stress range
$\Delta\sigma_m$	membrane stress range
$\Delta\sigma_s$	structural stress range
ΔS_s	equivalent structural stress range
$\Delta\sigma_p$	applied nominal stress range

welded joints [9]. It has been shown that fatigue of welded connections can be significantly influenced by joint misalignments which introduce secondary bending at the presence of axial tension on loaded intercostal members both in laboratory testing and in service conditions. More recent investigations, as thin plates are increasingly used for achieving lightweight in ship structures, include those on fatigue strength of laser welded thin plate structures using nominal stress and hot spot stress approaches [10], on secondary stress concentration resulted from thin plate initial flatness [11], and on assessment of three-