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Technical note

Numerical study on girth weld of marine steel tubular piles

Yi Li[a,*], Xiao-Peng Zhou[b], Zhao-Min Qi[c,1], Yi-Bo Zhang[b]

[a] National Inland Waterway Regulation Engineering Research Center and School of River and Ocean Engineering, Chongqing Jiaotong University, Chongqing 400074, China
[b] School of River and Ocean Engineering, Chongqing Jiaotong University, Chongqing, China
[c] Southwest Guizhou Vocational and Technical College for Nationalities, Guizhou, China

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A B S T R A C T

At a splice weld of marine steel tubular pile, the misalignments between two adjacent pile segments may cause significant stress concentrations. In structural analysis, the stress concentrations shall be properly addressed, normally by a stress concentration factor (SCF) in practice. Based on a flat-plate configuration, the SCF at pipe splice under either axial tension or in-plane bending moment has been theoretically derived. To verify the effectiveness of the flat-plate solutions, this paper investigated the SCFs with numerical modeling. Finite element models built by ANSYS were used to simulate pipe splices for different pile diameters and wall thicknesses, which are representative of practical marine applications. Axial tension and in-plane bending moment, as well as their combination were applied. The flat-plate solutions were compared with the numerical results. The results show that the flat-plate solutions are close to the numerical results, indicating that they are reasonably effective in practical applications under complex loading conditions. The findings will significantly help in the hot-spot analysis for splice welds of steel tubular members, particularly piles, in marine structures given complex loading effects. Additionally, an integrated formula including the effect of both axial tension and in-plane bending moment is formulated for the SCF at pile splice.

1. Introduction

In many cases, especially deep-water applications, marine steel tubular piles are prefabricated in tubular segments, and the segments are connected on site or in shop by transversal splice welds, namely girth welds [1,2]. As usual, geometrical misalignments between two neighboring tubular segments remain at the transversal splice, due to various sources including concentricity, out of roundness, thickness difference, and center eccentricity, as schematically illustrated in detail by Det Norske Veritas (DNV) [3]. For example, if two pile segments with equal wall thicknesses and diameters are connected, out of roundness and center eccentricity may be the major sources leading to misalignments, and Fig. 1 demonstrates such an example which occurred during in-situ welding process.

The misalignments may result in a considerable stress concentration effect on the hot spots at pile splice, thus increasing structural hot-spot stress and decreasing the fatigue strength of pile [4–6]. Hence the stress concentration effect should be appropriately considered in structural design. A practical way to estimate the structural hot-spot stress is to multiply the nominal stress at hot spot by a stress concentration factor (SCF). Because of the complex nature of the misalignments, i.e., uncertainties in on-site work and combined sources, analytic solutions to SCF are difficult to develop in most scenarios. Instead, approximate flat-plate solutions have provided a conservative, but robust method in practice for estimating SCF at pipe's butt weld.

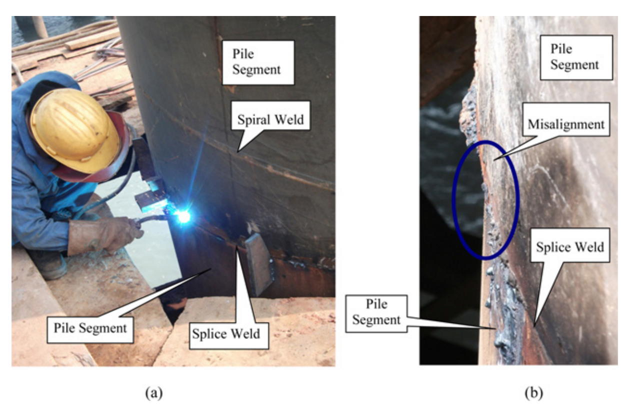

Fig. 1. Splice weld of a marine steel tubular pile: (a) field welding of pile splice and (b) observed misalignment between two segments.

The flat-plate solutions to SCF at pipe splices subjected to axial tension have been developed [7–9], and the wall thicknesses of connected segments can be equal or different in the solutions. More recently, Li et al. [10] derived a flat-plate solution given in-plane bending moment,

[1] Formerly, School of River and Ocean Engineering, Chongqing Jiaotong University, Chongqing, China

* Corresponding author. Tel.: +86 23 62652714; fax: +86 23 62650204.
E-mail address: yi.li@alumni.ubc.ca (Y. Li).

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Nomenclature

d	outside diameter of pipe segment
K_a	SCF at the outside maximum tension point (OMTP) under N
K_{am}	SCF at the OMTP under both N and M
K_m	SCF at the OMTP under in-plane bending moment
M	bending moment applied on the cross section at splice weld
N	axial tension applied on pile shaft
r_i	inside radius of tubular pile
t	wall thickness
δ	eccentricity between pipe segments
σ_a	nominal stress caused by N
σ_{b1}	additional tensile stress at weld toe due to N
σ_{b2}	additional tensile stress at weld toe due to M
σ_{hs}	structural hot-spot stress
σ_i	nominal stress at the inside edge caused by M
σ_n	nominal stress
σ_o	nominal stress at the outside edge caused by M
τ	thickness ratio

which is applicable to the case of equal wall thicknesses of connected segments. The flat-plate solution [10] significantly supports the practical fatigue assessment for marine steel piles under complex loading conditions, which typify deep-water applications properly. However, the solution derived by Li et al. [10] has not been verified by physical or numerical models.

With a series of numerical examples, this paper investigates the effectiveness of the flat-plate solutions, in particular that given in-plane bending moment. The flat-plate solutions are compared with the numerical results of finite element models built by ANSYS [11]. The numerical examples adopt representative configurations of practical marine steel pile design, such as weld form, diameter, and wall thickness. The loading effects of in-plane bending moment and axial tension are considered in the examples.

The remaining sections of this paper are organized as follows. In Section 2, both flat-plate solutions for axial tension and in-plane bending moment are reviewed, and an integrated formula combining both is derived. Then, the details of the numerical examples are described in Section 3. Numerical results are presented and analyzed in Section 4. Section 5 presents the conclusions.

2. Flat-plate solutions to SCF

For large-diameter steel pipes in marine and offshore facilities, segments are often connected by transversal V-shape butt welds made from outside without an inside backing strip [3,12]. To help in guiding the positioning of segments and guarantee welding quality, the use of inside backing strip is normally recommended in practice. The strip is attached on the lower segment by weak welds, for instance intermittent welds [13], and thus may not work structurally like stiffeners. Generally speaking, therefore, the inside backing strip can be actually ignored in structural analysis of splice weld.

Fig. 2 presents the typical configuration of a typical splice weld connecting two segments with equal wall thicknesses. A misalignment between two pipe segments is illustrated in Fig. 2(b), where t = wall thickness, and δ = the eccentricity between pipe walls. The pile diameters of both segments may be equal or different. Owing to the eccentricity, either the local tension around the weld or the global tension on the pipe shaft may introduce additional tensile stress in a certain region near the weld, i.e., stress concentration. The additional tensile stress reaches its maximum at the outside maximum tension point (OMTP). A weld toe of the butt weld, the OMTP is a critical

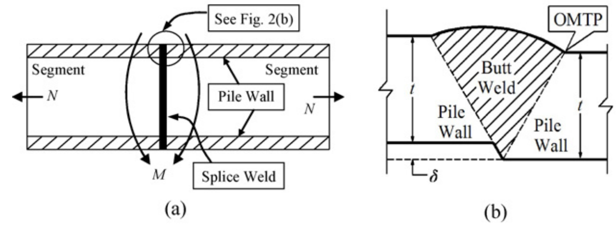

Fig. 2. Typical misalignment at splice weld: (a) splice and segments and (b) the misalignment between pipe walls.

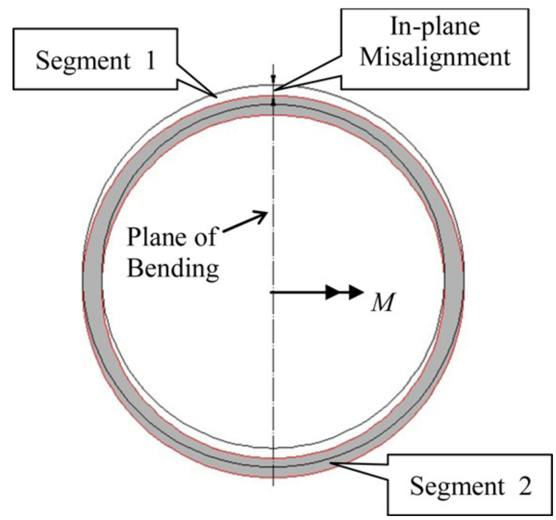

Fig. 3. The in-plane misalignment considered for the stress concentration given bending moment.

structural hot spot in the fatigue design of the weld. Despite a large number of parametric formulas for the SCFs at the tubular joints of offshore structures as summarized by Ahmadi et al. [14], the SCFs at pile splices have not been extensively investigated so far, and pipe splices are essentially different from tubular joints [8,10].

In general, the piles of marine structures are subjected to different loadings. This paper considers an axial tension applied on pile shaft (N), as well as a bending moment applied on the cross section where splice weld is positioned (M), as illustrated in Fig. 2(a). Field observations have informed that the segment misalignments at a pile splice randomly distribute around pile cross section, as reported in detail by Dailey et al. [6,15]. A bending moment in a certain direction may be in-plane for some positions on pile perimeter, but out-of-plane for the others. So far, the impact of in-plane bending moment on stress concentration has been investigated [10]. Specifically, the wall misalignment to be considered is located at a crown, for which M is an in-plane bending moment and yields maximum tensile bending stress. As an example, Fig. 3 displays such an in-plane misalignment point for two segments in center eccentricity.

For the case of equal wall thicknesses and pile diameters, Fig. 4 illustrates the stress distribution over wall thickness near the weld at in-plane misalignment point under N and M, where σ_a = the nominal stress caused by N, σ_o = the nominal stress at the outside edge caused by M, and σ_i = the nominal stress at the inside edge caused by M.

By the flat-plate assumption, the additional tensile stress at the OMTP due to N, σ_{b1}, is expressed as follows [7–9]

$$\sigma_{b1} = \frac{3\delta\sigma_a}{t} \quad (1)$$

While derived for double-side V-shape butt welds, Eq. (1) has been applied for single-side welds as a simple approximation. In Eq. (1), the nonlinear stress peak resulting from the local notch geometry of