Journal of Constructional Steel Research 112 (2015) 93–107

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Fatigue life enhancement of welded stiffened S355 steel plates with noncircular openings

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ARTICLE INFO

Article history:
Received 22 August 2014
Accepted 26 April 2015
Available online 19 May 2015

Keywords:
Stiffened plate
T-shape girder
Non-circular openings
Fatigue life
Residual stress

ABSTRACT

The paper is devoted to fatigue life enhancement of S355 steel welded stiffened plate containing T-shaped stiffeners and girders with non-circular openings. Its rounded corners are natural stress concentrators and potential places for initiation and growth of first-mode fatigue cracks. To slow down this process, beneficial residual compressive stresses are introduced around the non-circular opening corners through mandrel cold working of preliminarily drilled round holes in the corners' zone. The creation through cutting of the non-circular openings and subsequent welding of the T-shaped girders generates residual stress redistribution. The latter is studied both experimentally and numerically. X-ray diffraction method has been employed for residual stress analysis. The mandrel cold working process and subsequent cutting to form the non-circular opening have been simulated through a nonlinear finite element method (FEM) analysis. In order to simulate the residual stress redistribution due to welding of the T-shaped girders with non-circular openings, a sequentially coupled thermal-stress FEM analysis has been carried out. In order to identify the optimal value of the mandrel cold working interference fit (the difference between the mandrel diameter and the initial hole diameter) and welding sequence, a multi-objective optimization task is set and solved. The optimization has been based on a planned numerical experiment. The optimal value of the interference fit and the welding sequence have been found, which ensure high intensity and homogeneity of the residual compressive field around the opening roundings.

1. Introduction

The structures containing a plate reinforced by stiffeners are widely used in shipbuilding, the aircraft industry, bridges, offshore structures and other. They are particularly preferred in airframes, fuselages and winds of aircrafts, in structural components as ship decks and hulls for their high strength-to-weight ratio. This type of structure is subjected to intensive dynamic stresses, which provokes initiation and growth of fatigue cracks.

For strength and stiffness enhancement of the components as a whole, two types of structures are used: a plate, stabilized through welded to it stiffeners parallel to each other [1–4]; a plate, reinforced by welded longitudinal girders and transverse stiffeners [5–7]. T-shaped girders and stiffeners are used or such with other cross-sections. In the case of T-shaped girders and stiffeners, the structure could be made in two variants:

- The transversally placed stiffeners are welded bilaterally (or are not welded) to the T-shaped girders webs, so that their length is determined by the distance between the girders [5–8];
- In the webs of the T-shaped girders, non-circular openings are cut with a certain step, in whose openings the stiffeners are located [9].

Obviously, the structures comprising longitudinally situated T-shaped girders and transversely to them T-shaped stiffeners, provide high stability under bending in the two planes of inertia.

However, the use of non-circular openings provides the following advantages of the structure in comparison with the first embodiment:

- The bending stiffness of the structure is continuous in both principal planes of inertia as the high stability is provided mainly by the web of the T-shaped girders and the stiffeners.
- It is not necessary to weld the stiffeners ends to the web of the T-shaped girders. Thus, the structure assembly is achieved only by bilateral angular welds of the girders and stiffeners to the plate.

In order to correctly assess the load caring capacity and the fatigue behaviour of the corresponding structure it is necessary to take into account the following important factors:

- The influence of the imported after welding residual stresses;
- Stress concentration around fastener holes, openings, notches, slots, radii cut-outs etc.

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http://dx.doi.org/10.1016/j.jcsr.2015.04.018
0143-974X/

To adequately assess the structure fatigue life, reinforced through stiffeners, the experimental study based on fatigue tests is most appropriate. However, the implementation of this approach requires expensive specialized equipment and considerable resources of time and money. On the other hand, only certain components, containing stiffeners [2,3] or flat samples [10], may be subjected to fatigue tests.

The fatigue behaviour of the individual components with stiffeners is studied in two directions: the fatigue test type corresponds to the nature of the individual components loading [2]; the purpose of the fatigue tests is to study the development of pre-localized fatigue cracks in the plate [3]. When the fatigue tests are applied to flat samples, the emphasis is on the fatigue characteristics of a concrete steel, not on the fatigue behaviour of the corresponding structural component [10]. Obviously, this approach can not be applied to a single structure, containing a plate with T-shaped girders and stiffeners. From this viewpoint, an alternative approach to assess the fatigue behaviour of the structural components is knowing in a qualitative and quantitative aspect the residual stresses in potentially critical areas in the corresponding structure.

When the structures are made of aluminum alloys, alternative assembly methods are used—riveted or adhesive bonded stiffeners [3]. As a whole, these methods are used mostly in the aircraft industry. In case of stiffened steel plates, often found in ship structures, offshore structures etc., complex residual stresses are imparted, which are caused by the heating and cooling effect of the welding process. For their study, two main approaches are applied—an experimental one, based on neutron diffraction strain-scanning technique, X-ray diffraction or hole drilling measurement [3,4,11] and a finite element method (FEM) [3,4,9,12–14]. A number of studies of weld steel structures with stiffeners confirm that near the welds, tensile residual stresses are generated, caused by intense local heating, followed by cooling due to the heat transfer to the environment [3,11–13]. In this aspect, the welding of the stiffeners to the web of the T-shaped girders will cause pronounced local effect areas with tensile residual stresses in the web of the girders. If these welds are eliminated, the structure stiffness will be discontinuous, which will significantly reduce its load carrying capacity. As it is known, tensile residual stress fields are potential sites for initiation and growth of first-mode cracks, when the maximum working stresses are tensile and vice versa—the fatigue crack growing process is significantly slowed when the residual stresses are compressive [2,3,9,12–14]. From the viewpoint of the fatigue life and safety during operation, a disadvantage of the structure containing T-shaped girders with noncircular openings are the rounded places because they are natural stress concentrators (Fig. 1).

According to [9], the stress concentration at the edge of a cut-out may be limited to about four times the nominal stress in the region. Therefore, taking into account a considerable stress-concentration,

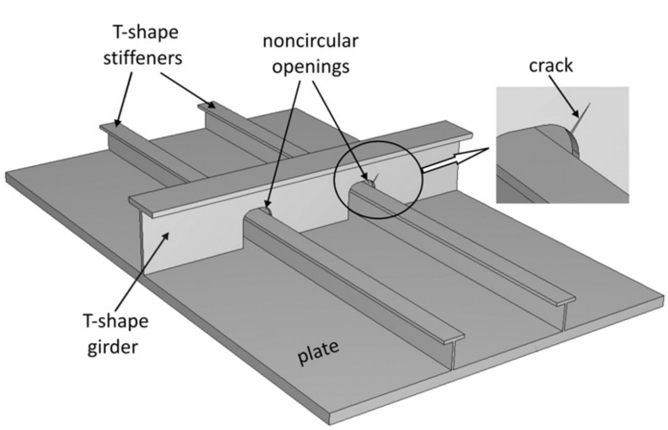

Fig. 1. Stiffened structure with non-circular openings.

the rounded corners are potential places for initiation and growth of first-mode cracks. As it is well-known the fatigue life of metal structures can be increased by generating compressive normal stresses around the stress concentrators. These beneficial residual stresses significantly reduce the maximum values of the operating tensile stresses arising at the critical points of the members and in such manner, impede the formation of the first-mode fatigue cracks.

A common approach to impart beneficial residual stresses is the cold working process, having a temperature lower than the recrystallization temperature of the respective metal. When the stress concentrator is a circular hole, fastener or other, the cold working can be carried out through various methods: ball or solid mandrel expansion [16], ring coining [17], pre-stressing of fastener holes by tapered pin and tapered sleeve [18], pad coining [19], split sleeve cold expansion [20], cold working by seamless tubular member [21], split mandrel cold working [22], stress wave [23], cold work of holes by rotational mandrel and tubular seamless sleeve made of shape memory alloy [24] and others.

For cold working of noncircular openings, an initial mechanical surface treatment such as ball and roller burnishing, shot peening, stress coining and others, has been employed. For instance, in the case with a transverse web-frame (Fig. 1), after welding of the web-frame to the plate, stress coining has been employed in order to introduce beneficial compressive stresses around the cut-out corners [9]. In the case of aluminum alloy, experimentally and through FEM analysis, it has demonstrated the beneficial effect of stress coining on the structure fatigue life.

Taking into account the nature of the ball and roller burnishing, shot peening and stress coining, they are characterized by a common disadvantage—relatively shallow zones of residual stresses imparted around the openings. From this point of view these methods are most effective for aluminum alloys. Considering the wide application of steel, obviously, in the case of structure with noncircular openings (Fig. 1), another solution is necessary, in order to generate more intensive and deeper zone with compressive residual stresses. A suitable material for building the depicted in Fig. 1 structure is constructional low-alloy steel S355 EN 10025-1:2005.

Using the advantages of the cold hole expansion method, Landy and Easterbrook [25,26] developed methods for fatigue life enhancement of noncircular openings: by means of cold expansion of circular holes, preliminarily drilled at appropriate places and next cutting of the unneeded metal to obtain a noncircular opening [25]; by means of cold expansion of the noncircular opening using appropriate insert [26]. A main disadvantage of the method [26] is the need of a complicated tool, composed of parts with external (covering) contour, corresponding to that of the non-circular opening. On the other hand, technologically, there are various possibilities for implementation of the process of cold working of the pre-drilled holes in the rounded areas in accordance with the basic idea of the method [25]: solid mandrel expansion [16]; split mandrel cold working [25]; direct mandrel cold working etc. These methods have a common disadvantage—significant and nonsymmetrical, with respect to the middle plane of the plate, gradient of the generated residual stresses due to axial force flow passing through the mandrel-plate-support system [27,28]. On the other hand, because of the relatively close location of the pre-drilled holes, an effect of interference between the plastic and elastic waves, generated due to the cold working of the two holes, is observed [29]. Taking into account the aforementioned features, it is necessary to find the optimal interference fit and the working scheme for the implementation of the mandrel cold working process of the pre-drilled holes.

The main objective of this study is to estimate the beneficial effect from implementation of cold working on S355 steel of preliminarily drilled holes in corner zones of noncircular opening and next cutting to obtain a noncircular opening in accordance with the configuration shown in Fig. 1.