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# Fatigue assessment of welds joining corrugated steel webs to flange plates

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ABSTRACT

This paper presents an analytical approach for the fatigue assessment of welds joining corrugated plates to flange plates. The failure mode, stress distribution and fatigue strength of such welded joints have been examined through experimental tests and finite element analyses. As the stress concentration at the external weld line of the transition curvature is very critical for the fatigue life assessment, the study of such geometric effect has been performed and its resultant stress characteristics are discussed. The results show that, for the stress concentration at the fatigue critical point of the transition curvature, the influence of the corrugation/curvature angle is more significant when the ratio of the curvature radius to the corrugation depth is smaller, and vice-versa. The *S–N* curve of referred cruciform joint details can be regarded as the lower bound in contrast to the fatigue strength of welded joints with varying corrugation angle. Allowing for the combined stress condition, the proposed analytical approach is demonstrated to be appropriate for the fatigue assessment of the welded joint with the corrugated plate. The consideration of residual stress in the proposed analytical model is also discussed in theory.



## 1. Introduction

Corrugated steel web plate with the merit of sufficient out-of-plane stiffness has gained increasing application in highway bridge girders [1]. Configuration geometry of the corrugated web consists of folds parallel and inclined to the longitudinal direction of the beam. In the connecting detail, the corrugated web (1) joins the flange plate (2) through the fillet weld (3), as shown in Fig. 1. When the corrugated steel web girder is subjected to bending, the stress flow on the flange plate is inherently affected by the variation of the corrugation and its related welded details. The weld defects and stress concentrations due to geometric changes may trigger fatigue cracks in the girders. The understanding of the fatigue behaviour of the welded joints is, therefore, necessary for the design of the corrugated steel web girder with the consideration of its long term structural response.

Several fatigue experiments [2–7] have been performed recently on the corrugated steel web girder specimens in beam form. Based on these experimental results, the fatigue failure mode at the web-to-flange welded joints has been reported and the fatigue strengths were compared with respect to codified fatigue detail categories. The fatigue test results to account for welded details are, however, still limited due to the fact that, the beam specimens are often not only involved with more complex stress conditions in the flange and web relating to the stress variation through its thickness and combined action of bending and shear respectively; but also involved with complicated local geometric details.

Since the welded details used in the beam design are essentially similar regardless of the size, it is necessary to consider separately the effect of local details on the overall structural fatigue resistance [8]. The point of this consideration has been widely adopted in current research work, e.g. the studies for welded tubular *K*-joints [9], welded thin-walled CHS–SHS *T*-joints [10], welded trapezoidal joints [11], etc. Specially, the fatigue strength of welded joints have been investigated in former extensive research [12–14] from the specimens with gussets longitudinally and transversely welded on the main plates as a basis and then given in the form of *S–N* curves for welded details in relevant fatigue design codes [15–17]. To allow for the welds under combined normal and shear stress condition, Yamada et al. [13,18,19] and Kim and Yamada [20] conducted experimental and numerical studies on the behaviour of inclined non-load-carrying fillet welded joints. The inclined weld angles to the longitudinal stress direction mostly chosen in aforementioned studies were no less than 45° which are quite larger than corrugation angle in general practice. It is therefore not

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**Nomenclature**

*Special symbols adopted are not summarized below, but their explanations are included in the text*

- $A'$ multiplier for fatigue crack propagation rate equation
- $A'_{no}$, $A'_{com}$ $A'$ corresponding to nominal and combined stress ranges respectively
- $a_{ff}$ fillet weld leg dimension
- $a_l$ crack length
- $a_i$, $a_f$ initial and final crack depths respectively
- $b_0$ width of main (flange) plate
- $C$ material constant
- $CAFT$ constant amplitude fatigue thresholds
- $F_S$ free surface correction factor
- $F_E$ crack shape correction factor
- $F_r$ correction factor related to residual stress for various crack locations
- $F_T$ finite thickness correction factor
- $F_G$ geometry correction factor
- $F_{G,n}$, $F_{G,tl}$ $F_G$ corresponding to remote nominal stressed region and local transition curvature respectively
- $h_c$ depth of corrugation
- $HSC$ highest stress concentration
- $k_o$ overall stress concentration factor
- $k_w(x)$, $k_{ts}(\theta)$ stress concentration factors related to weld profile and $\theta_{smax,i}$ respectively
- $K_m$ applicable fracture toughness for the material and thickness
- $K_n$, $K_r$ stress intensity factors related to nominal tensile stress and residual stress respectively
- $K_c$ combined stress intensity factor with nominal tensile stress and residual stress
- $K_{n,max}(K_{n,min})$ stress intensity factors corresponding to maximum and minimum nominal stresses
- $l_l$, $l_i$ lengths of longitudinal fold and inclined fold respectively
- $m$ slope of the $S$–$N$ relation
- $N$ the number of cycles to failure
- $N_p$ fatigue crack propagation life
- $N_{p,no}$, $N_{p,com}$ $N_p$ corresponding to nominal and combined stress ranges respectively
- $O'$ centre of curvature
- $R(R_c)$ nominal(combined) stress intensity ratios
- $R_t$ curvature radius
- $s$ standard deviation
- $t_f$ thickness of main (flange) plate
- $t_w$ thickness of corrugated (web) plate
- $Y_r$ function depending on the geometry of the crack
- $\theta_c$ angle of inclined fold to stress in longitudinal direction
- $\theta_t$ centre angle of transition curvature
- $\theta_{tsmax,i}$ centre angle relating to the maximum principal stress at external curvature
- $\gamma$ ratio of $R_t$ to $h_c$
- $\upsilon$ Poisson's ratio
- $\Delta\sigma_i$ applied stress range
- $\Delta\sigma/_{2\ \text{million cycles}}$ calculated stress range at 2 million loading cycles
- $\Delta\sigma_n$, $\Delta\sigma_t$ normal and tangent stress ranges for the point at the transition curvature respectively
- $\Delta\sigma_n$, $\Delta\sigma_{com}$ stress ranges corresponding to $N_{p,no}$ and $N_{p,com}$ respectively
- $\Delta K$ ($\Delta K'$) nominal (modified) stress intensity factor ranges
- $\Delta K_n$, $\Delta K_t$ stress intensity factor ranges corresponding to $\sigma_n$ and $\sigma_t$ respectively
- $\Delta K_c$ stress intensity factor ranges corresponding to $K_c$

sufficient to import these reported results for the assessment of the welded joints with corrugated plates. Anami and Sause [21] performed finite element analyses and simple crack propagation analyses of the web-to-flange welds of the corrugated steel web girders with calibration to a standard fatigue design curve. The fatigue life prediction in this referred report was suggested and its accuracy was affected with the variation of the fatigue critical point with respect to the longitudinal fold. Regarding the fatigue assessment of such welded joints, one can conclude that the main challenge lies in the fact that the transition curvature part is geometrically irregular which poses difficulty in using related parameters of the longitudinal fold and the inclined fold of the corrugation for its characterization. Also, the problem is further complicated by

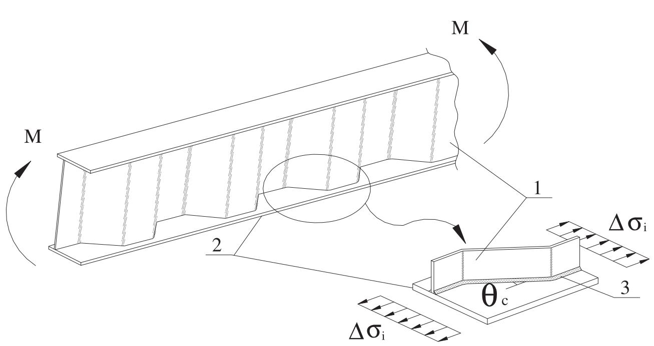


**Fig. 1.** Illustration of a welded joint with corrugated plate.

combined stress field along the transition curvature part with respect to the direction of applied stress.

The following sections present a fatigue experimental study and finite element analysis on the fillet welded joints with corrugated plates. The corrugation angles were intentionally varied as in common use between 30° and 60° to the principal stress in the longitudinal direction. The parametric study based on the developed finite element models was conducted to find the geometric effect on the stress concentration along the weld toe. Thereafter, the fatigue critical point at the transition curvature part is determined considering the curvature centre angle and the ratio of the curvature radius to the corrugation depth. An analytical approach to allow for combined normal and tangent stress ranges at the fatigue critical point is proposed and compared with reviewed test data. The introduction of residual stress in the analytical model is also discussed in a theoretical analysis.

## 2. Description of fatigue tests

### 2.1. Specimens and material

The basic configuration of a half-unit of the corrugation and its related welded details is illustrated in Fig. 2. The longitudinal fold (range 1) and the inclined fold (range 3) are joined together through the transition curvature (range 2). The parameters given for the transition curvature are the centre angle ($\theta_t$) and the ratio ($\gamma$) of the curvature radius ($R_t$) to the depth of corrugation ($h_c$). The corrugation angle ($\theta_c$) is defined as the angle of the inclined fold to the stress in longitudinal direction. Since the longitudinal