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Exploring Size Effects in the Fatigue Behaviour of Lightweight Welded Structures

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Abstract

Lightweight structures play a crucial role in various industries, where reduced component thickness enables improved performance, increased load capacity, and a lower environmental impact. High-strength steels (HSS) are key factors of such designs due to their superior static and fatigue properties; however, their fatigue performance is strongly governed by welding, as welded joints typically represent the weakest region of a structure. Among the parameters influencing fatigue life, in the current study, the size effect, including both the thickness effect and the thinness effect, together with weld quality, is of particular importance.

This work investigates the influence of plate thickness and weld quality on the fatigue strength of welded joints through a combined experimental, numerical, and probabilistic approach. Fatigue test series were performed on transverse non-load-carrying attachments with plate thicknesses ranging from 2, 8 and 16 mm under uniaxial constant-amplitude loading. Local weld geometry and angular misalignment were measured using laser scanning, enabling detailed quantification of geometric variations along the weld seam. These measurements were incorporated into fatigue assessment and weld quality evaluation.

The results demonstrate a pronounced thinness effect, with thinner plates exhibiting an increase in fatigue strength, highlighting the limitations of existing fatigue design procedures that primarily account for reductions in strength for thicker plates. Weld geometry also plays a critical role, as larger weld-toe radii and weld-toe angles, along with reduced misalignment, contribute significantly to lower stress concentrations and extended fatigue life. The Effective Notch Stress (ENS) method and weakest-link probabilistic modelling were applied to capture local stress distributions and quantify their influence on fatigue failure.

Overall, the study provides a deeper and more comprehensive understanding of the combined influence of plate thickness and weld geometry on fatigue strength. The findings support the industry in designing lighter, high-performance products with a lower carbon footprint, ultimately contributing to more sustainable welded structures.

Keywords

Welded Joints, Fatigue, Size effect, Thickness effect, Thinness effect, Probabilistic modelling, Weld quality, Finite element analysis.

1. Introduction

The reduction in fatigue capacity of welded components with increasing plate thickness, commonly referred to as the size effect, is widely recognised in most fatigue design standards. The size of the main load-carrying plate and transverse attachment, in addition to weld size, are the main contributing factors in this matter [1]. Thus, the thickness correction formula, based on a reference thickness and power exponent, is employed to reflect the size dependence of fatigue strength. Fatigue design codes and recommendations account for the thickness effect by lowering the S–N curve for joints exceeding the reference thickness [2]. Conversely, potential increases in fatigue strength for thinner plates are often overlooked, even though reducing the material thickness below the reference value leads to higher fatigue strength, a behaviour known as the thinness effect [3].

Lightweight structures are beneficial among industries, as thin components can, for example, enhance performance, and payload capacity. In this context, lightweight design aims for high-performance and stiff structures, but challenges in materials, manufacturing, and cost require effective design methods to accurately predict and improve structural performance [4, 5]. It should be noted that to ensure structural integrity, the welded structures are usually designed against common failure modes such as ductile failure and fatigue failure. The use of thin high-strength steels (HSS) provides significant potential for weight reduction, which is desirable in many engineering applications; however, the advantages of reducing weight also come with challenges. Ensuring structural integrity and durability becomes particularly important, as thin-walled sections are more likely to experience issues such as local buckling, fatigue, and other mechanical failures. These concerns are even more pronounced in welded components made of HSS, where weld quality strongly influences performance. Therefore, careful design, accurate calculation, and accurate failure assessment are essential to fully utilise the benefits of thin plate HSS structures, considering the need for safety and reliability. In addition to higher static strength, these types of steels provide enhanced fatigue resistance due to their microstructure. However, realising these benefits depends on design and fabrication methods [6]. Fig. 1 shows fatigue strength utilisation of base metals for different designs and details. As shown, the as-welded joints rarely benefit from high-strength steels. Therefore, improving weld quality, applying post-weld treatments, or reducing plate thickness is necessary to take advantage of their properties. The latter approach is the focus of the current study.

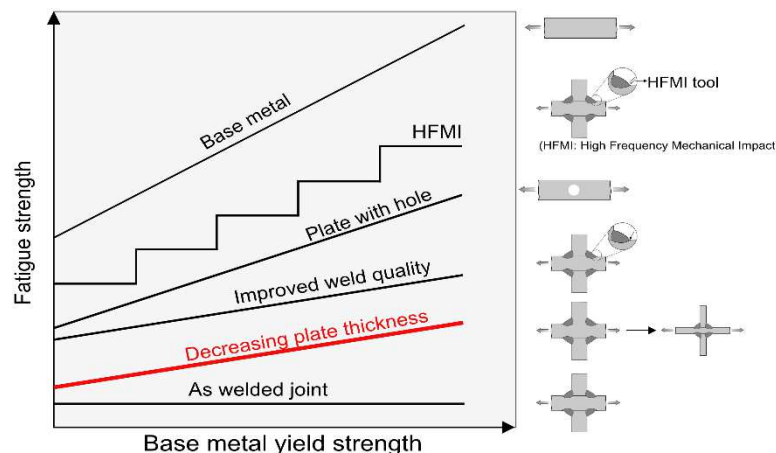


Figure 1. Fatigue strength with respect to yield strength of steel plate and welded joints.

In thin plates, weld quality plays a crucial role in fatigue performance. Weld imperfections and defects lead to localised stress concentrations in the vicinity of the weld. Several studies have attempted to evaluate weld quality by incorporating the actual weld profile into numerical analyses. Hultgren et al. [7] examined the relationship between weld geometry parameters such as leg length, toe radius, undercut, and toe angle and fatigue life using laser-scanned weld profiles. In a subsequent study real weld geometries were integrated into fatigue assessments together with weakest-link modelling approaches, resulting in reduced variation in fatigue life predictions [8].

Systematic investigations about the thinness effect are scarce, particularly for implementation into international standards, guidelines and technical documents. Hence, the research within this study is motivated by carrying out comprehensive deterministic and probabilistic analysis along with experimental processes like fatigue testing in order to develop robust design recommendations for thin-walled welded structures beyond those found in today's international standards. The aim of the work is to investigate thickness and thinness effects on fatigue strength of welded joints, with the overall goal of developing structural reliability assessment methods that support industry in designing lighter, high-performance products with a lower carbon footprint, ultimately contributing to more sustainable welded structures. This study examines how thin plate geometry and weld quality influence the fatigue performance of transverse non-load-carrying attachments. By analysing fatigue test data alongside detailed weld profile measurements obtained through high-resolution laser scanning, the research clarifies the sources of variability in fatigue life and the relationship between fatigue strength, plate thickness, and weld quality. Because current fatigue design rules are primarily focused on thicker plates and offer limited guidance for thin-walled structures, their applicability remains uncertain. To address this gap, fatigue tests on thin welded joints are combined with finite element analysis to investigate the thinness effect and the increased sensitivity of thin plates to imperfections such as misalignment.

2. Methodology

2.1. Effective notch stress approach

The effective notch stress is a local method for fatigue assessment at the weld root and toe. The method is derived from the Neuber approach [9], where the stress is averaged over the microstructural length of the notch ligament. Radaj [10] applied this theory to welded components by using Eq.(1). Assuming that the actual weld radii are $r_{real} = 0$ mm (considering a sharp transition as a worst-case scenario), the factor $s = 2.5$ (derived for von Mises stress hypothesis) and notch ligament $\rho^* = 0.4$ mm results in a fictitious radius of $r_{ref} = 1$ mm at failure locations, toe and root, as shown in Fig. 2.

$$r_{ref} = r_{real} + \rho^* \cdot s \quad (1)$$

In order to obtain accurate results, certain recommendations for notch discretisation, including the element size, have been provided in the IIW recommendations. In the IIW recommendations for weld toe and root, different values of r_{ref} are proposed depending on plate thickness. The effective notch stress is then compared with the corresponding FAT value to assess fatigue performance [2].

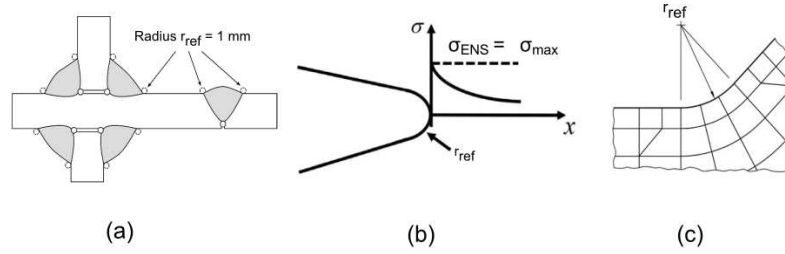


Figure 2. Effective notch stress method: (a) Fictitious rounding of weld toe and roots, (b) Stress distribution, (c) Recommended meshing at weld toe [2, 11].

2.2. Probabilistic approach

Variability in manufactured components makes fatigue prediction challenging. Probabilistic approach, such as weakest-link modelling, addresses these variations by using statistical and probability modelling. The concept underlying the weakest link theory was developed by Weibull [12]. The weakest link method can be described through a chain, in which the failure of the weakest link causes the failure of the entire chain. This implies that the overall failure probability of the model is determined by combining the individual link failure probabilities. In other words, the model's fatigue strength is determined by the weakest region of the specimen. The failure probability of the considered structure is described by Eq.(2):

$$p_f = 1 - \exp\left[-\iint_A \left(\frac{\sigma}{\sigma_0}\right)^\beta \frac{dA}{A_0}\right] \quad (2)$$

In this equation σ is fatigue driving stress that applies to each sub-area dA in the weakest-link area model. Parameters σ_0 and A_0 are characteristic fatigue strength and reference area, respectively, and β is the Weibull shape parameter. The fatigue driving stress can be expressed in the form of weighted (weighted to reference area, A_0) average of surface stress, namely equivalent stress, σ_{equ} , as explained in Eq.(3) [8]:

$$p_f = 1 - \exp\left[-\left(\frac{\sigma_{equ}}{\sigma_0}\right)^\beta\right] \quad (3)$$

where the value of σ_{equ} is derived based on Eq.(4). The specimen stress, calculated in finite element modelling, is shown as σ .

$$\sigma_{equ} = \left(\iint_A \sigma^\beta \frac{dA}{A_0}\right)^{\frac{1}{\beta}} \quad (4)$$

The sectional stress component, subsequently derived from the stress amplitudes in each weld section, is shown for two specimens in Fig. 3 [8]. It can be seen that, despite higher nominal and equivalent stresses in one case, the sectional stresses are greater in the other, emphasizing the influence of weld geometry on local stress distributions.

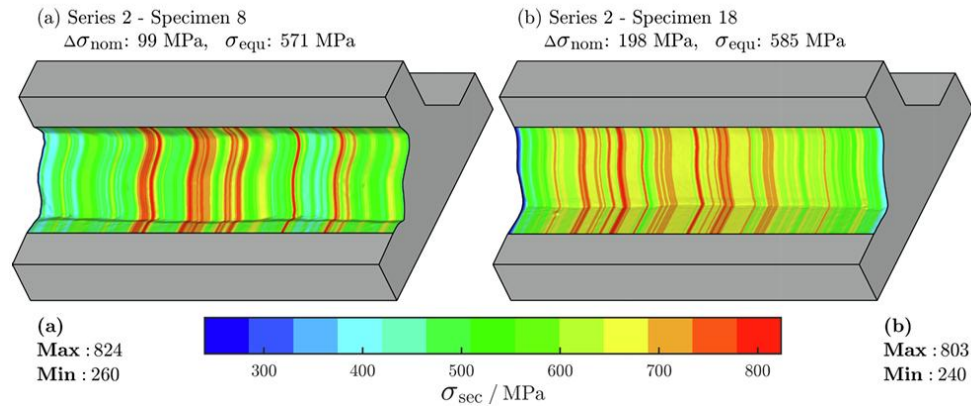


Figure 3: Sectional stress distribution for two specimens, representing the most critical locations along the weld [8].

Fig. 4 illustrates that, based on the fitted Weibull shape parameter, the probabilistic method yields lower scatter in equivalent stress compared to the nominal stress method [13, 14].

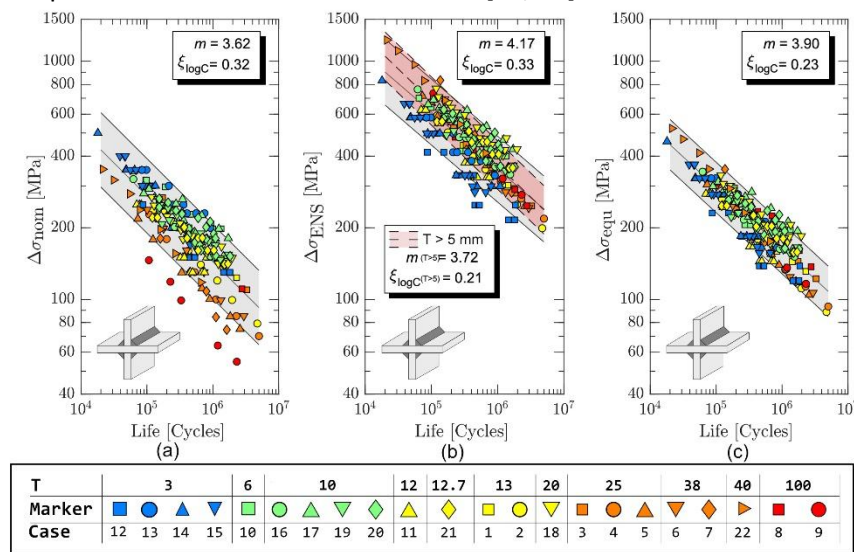


Figure 4: S-N curve for transverse non-load-carrying welded attachments with plate thickness denoted as T , (a) Nominal stress, (b) Effective Notch Stress, (c) Probabilistic Stress [13, 14].

3. Weld quality assessment

Fatigue life can be enhanced by the improvement of weld geometry. As a matter of fact, the variation of weld geometry is a fundamental factor in weld quality assessment and is the key factor affecting scatter in the fatigue strength of welded components. Therefore, analyzing and better understanding of weld quality and weld geometry can improve the accuracy of fatigue strength predictions. That means the weld surface and internal defects show how a weld can meet the requirements for the service life of the components. Here, the local defects govern fatigue strength, which means fatigue-loaded structures require high weld quality. This is more highlighted in the case of welded components composed of high-strength steel. Although using high-strength steel allows weight reduction by thinning load-carrying members and a lightweight design, such steels are more sensitive to geometric defects, which makes weld quality assurance challenging in high-strength steel applications. In this context, quality standards such as the Volvo standard STD 181-0004 [15] and the international standard for weld quality ISO 5817:2023 [16] set some requirements for weld quality classification. Weld toe geometry could be evaluated using manual gauges by visual inspection. However, this approach is ineffective or outdated if the measurement systems are not adequately evaluated to capture the true variations

in production [17]. To avoid these problems, vision systems in a computerized environment are introduced, in which the surface of the weld is scanned and analyzed by a laser scanner [18], as shown in Fig. 5. This approach allows for a highly accurate evaluation of the correlation between weld geometry and stress raisers.

Using digital measurement systems helps to identify weld discontinuities and geometric imperfections with high precision, which impact both safety and cost of the components. Accurate detection and improvement of weld defects are especially important because they are closely linked to fatigue strength, considering fatigue failures are often governed by local defects. In practice, weld geometry varies stochastically due to unavoidable variation in manufacturing and welding processes. A major limitation is that the variability of weld geometry is not considered in many technical documents, as the finite element analysis uses an idealized weld geometry, and fatigue strength relies on recommendations which are based on testing results.

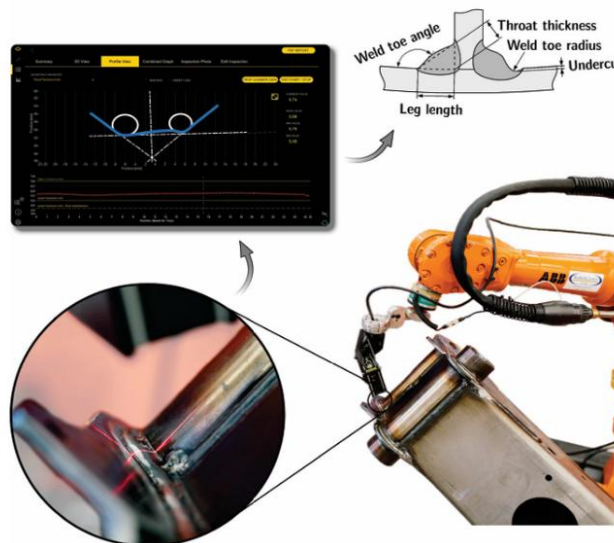


Figure 5: Implementing the quality assurance system Winteria® to capture the variation of weld geometry along the weld seam [6].

The measured variations in weld geometry parameters were evaluated in [19, 20], and imperfection limits by quality level B and C are defined according to ISO 5817, as depicted in Fig. 6 and Fig. 7. The T2B, T2C, T8B, T8C, T16B, and T16C labelling methods distinguish series, with “T” denoting plate thickness and the final letter indicating weld quality. A reduction in weld quality from level B to level C is accompanied by decreases in both weld toe radius and weld toe angle, which results in a sharper transition between the weld and the base plate. These geometrical changes increase the stress concentration at the weld toe region, which can considerably affect fatigue performance.

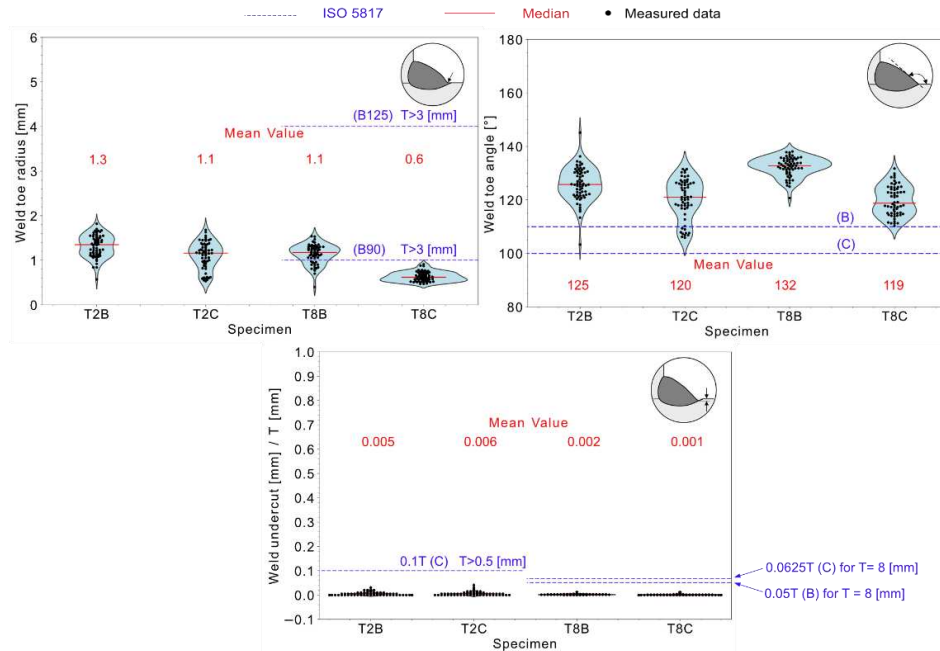


Figure 6: Variation of local weld geometry parameters for plate thicknesses of 2 mm and 8 mm [19].

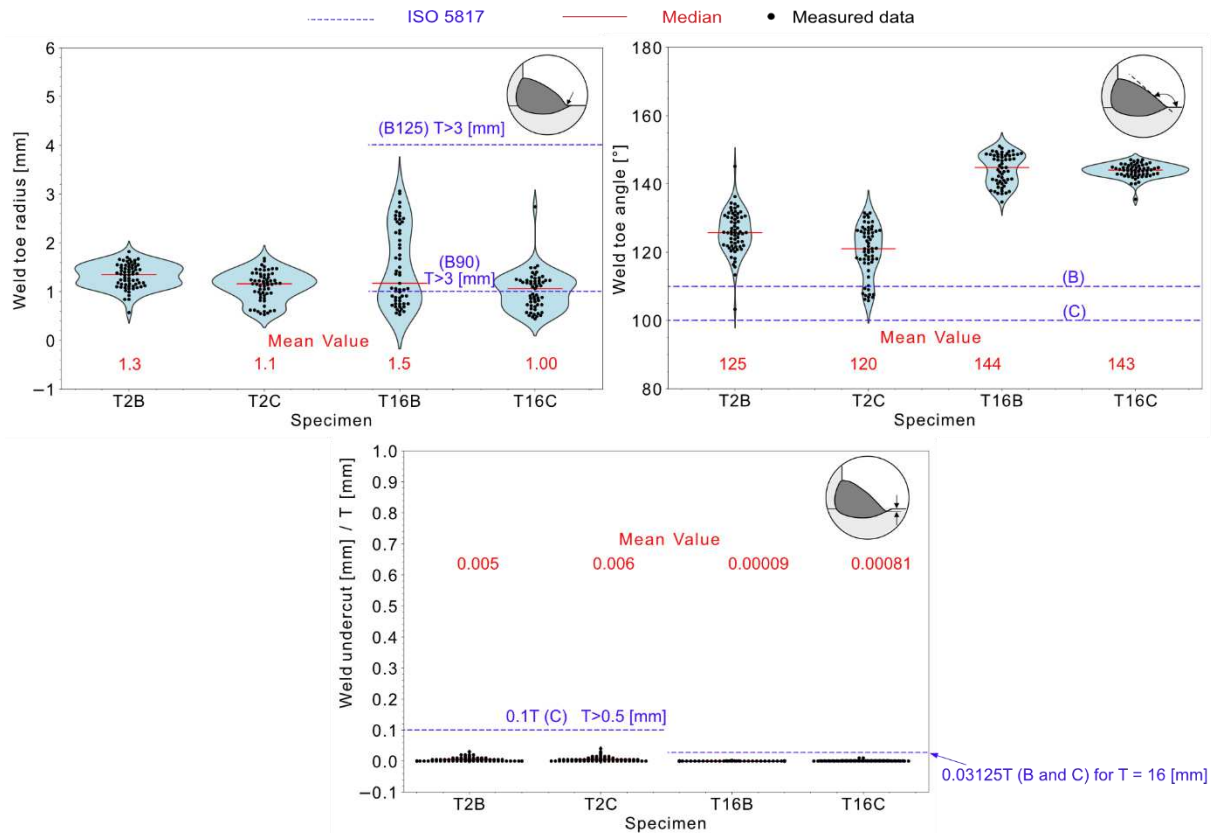


Figure 7. Variation of local weld geometry parameters for plate thicknesses of 2 mm and 16 mm [20].

The weld micrographs as shown in Fig. 8 show that a single-pass weld suffices for 2 mm and 8mm specimens, while 16 mm specimens require three passes to ensure proper penetration, minimize defects, and control residual stresses and distortion, improving overall weld integrity. Comparison of geometrical features reveals

that the 2 mm welds have larger toe radii, whereas 16 mm welds have larger angles. Weld quality C exhibits smaller toe angles than weld quality B.

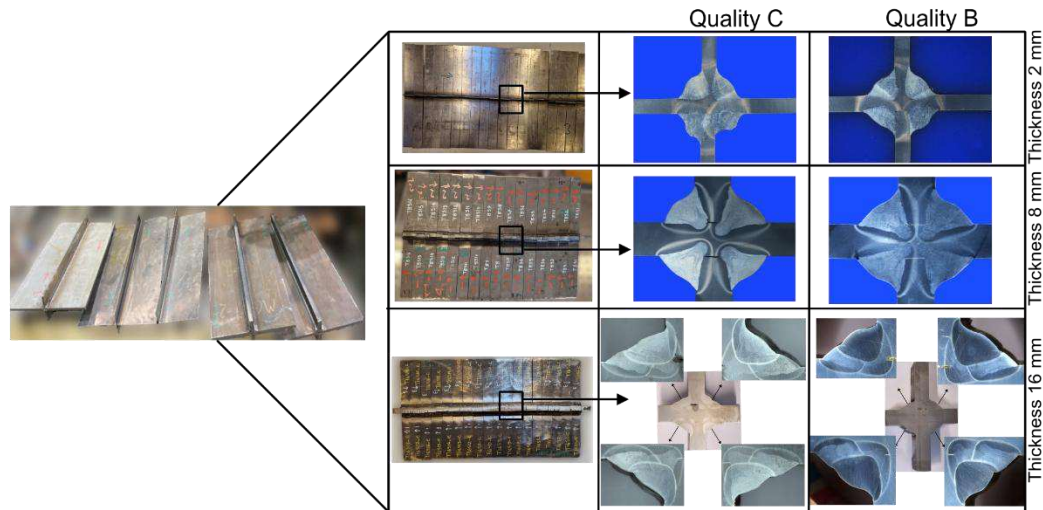


Figure 8: Cross-sectional micrograph of test specimens[19, 20].

4. Size effect in fatigue

Fatigue strength is known to be size-dependent for both notched unwelded [21] and welded specimens [1]. The size of the primary load-bearing plate, together with transverse attachments and weld geometry, plays a key role in determining the fatigue behaviour of welded joints. Increasing plate thickness has both positive and negative effects. Positively, increasing thickness reduces misalignment, allows longer crack growth, and makes the statistical size effect depend more on weld length than thickness. Negatively, if the weld toe geometry is unchanged, stress concentration and crack-tip stresses increase with thickness, while residual stress may be lower in thin specimens. Note that these effects are mostly observed in small-scale specimens and may not apply to actual components [22].

The influence of plate thickness on welded joint fatigue behaviour can be divided into three key effects: geometrical size effect, statistical size effect and technological size effect, as shown in Fig. 9, which are outlined as follows:

4.1 Geometrical size effect

The geometrical size effect could be expressed with respect to the stress gradient through thickness along the crack propagation path caused by geometrical discontinuities, bending or torsional loads. For the geometrical size effect, the stress gradient through thickness at the weld toe is more evident under bending loading, which becomes steeper in thinner joints. Consequently, at the same nominal stress level, as the plate becomes thinner, a small crack near its surface experiences lower stress [22].

4.2 Statistical size effect

Considering statistical size effect, large volumes tend to include more defect zones. Owing to the fact that fatigue represents the weakest link process, failure initiates at the part of the component, which is most susceptible to failure, for example, in the weld imperfection and stress concentration regions [23]. Consequently, an increase in the number of weak regions may raise the probability of fatigue failure.

4.3 Technological size effect

Size effect could also arise from the manufacturing process, which is called the technological size effect. This implies that the manufacturing process may alter the mechanical properties of the component. Examples of this include residual stress and misalignment. In this context, the higher residual stress observed in thicker plates due to constraints against thermal contraction, as well as variations in microstructure and surface roughness, can be interpreted as a technological size effect [3, 22, 24].

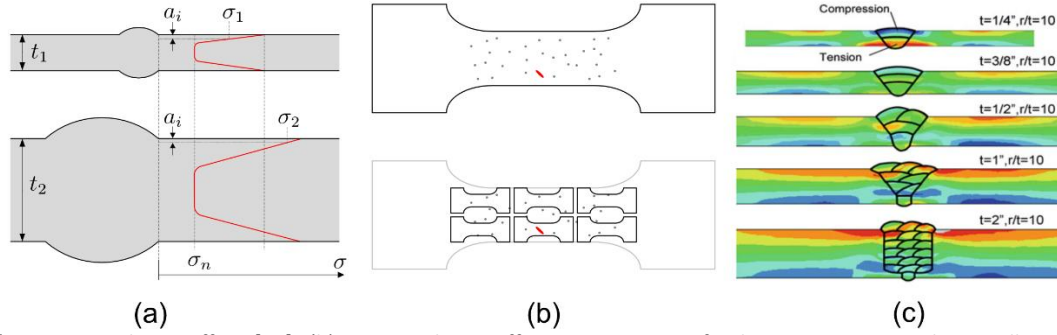


Figure 9: (a) Geometrical size effect [22], (b) Statistical size effect: comparison of a large specimen and a small specimen [22], (c) Technological size effect (axial residual stress) [25].

Thickness reduction in load-carrying structures subjected to fatigue loading has substantial potential to gain fatigue life. Such influence, referred to as the thinness effect. The fatigue strength of thin-walled structures has been extensively investigated in numerous studies within different fields such as the automotive and shipbuilding industries. Interest in this topic dates back several decades, when pioneering researchers such as Gurney [1, 26] and Maddox [27] demonstrated that, among the variables influencing the fatigue strength of welded components, specimen size plays a critical role. It has been shown that increasing plate thickness results in a reduction in fatigue capacity of the component. In addition to base plate thickness, Gurney [1] also accounted for the attachment thickness and weld size in the fatigue capacity calculations. He proposed the thickness correction formula, as presented in Eq.(5) to improve the accuracy of fatigue strength predictions.

$$S = S_B \left(\frac{t_B}{t} \right)^{1/4} \quad (5)$$

In this formula, S is the fatigue strength of the joint with thickness t , S_B is the fatigue strength of the joint with reference thickness t_B corresponding to the S-N curve. Gurney [1] also suggested that the reference thickness of $t_B = 32 \text{ mm}$ for tubular nodal joint and $t_B = 22 \text{ mm}$ for other joints and 0.25 for the thickness exponent. In line with the outcomes reported in prior studies, the thickness correction factor has been applied across several standards and technical documents, such as IIW recommendations [2] and the SSAB design handbook [28], yet exhibiting different values of reference thickness and thickness exponent. In IIW recommendations, the thickness reduction factor is introduced to reduce the fatigue strength of welded joints when the wall thickness exceeds a reference thickness $t_{ref} = 25 \text{ mm}$. The thickness reduction factor is expressed by Eq.(6) [2]:

$$f(t) = \left(\frac{t_{ref}}{t} \right)^n \quad (6)$$

In this formula, t is the thickness of the load-carrying plate, t_{ref} is the reference thickness and n is the thickness exponent. The values of n varies depending on structural details. For plates with transverse attachments, the thickness reduction factor depends on the weld toe distance L , as depicted in Fig. 10.

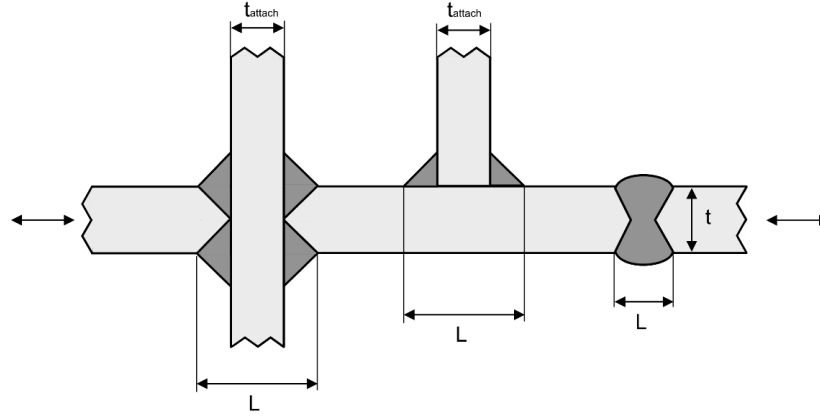


Figure 10: Definition of toe distance [2].

If the toe distance is not known, $L = 2 \cdot t_{attach}$ should be considered. Then the thickness reduction factor is calculated according to Eq.(7) [2]:

$$f(t) = \left(\frac{t_{ref}}{t} \right)^n \left(\frac{t}{t_{attach}} \right)^{0.1} \quad (7)$$

with $f(t) \leq 1$ and $\frac{t_{attach}}{t} \leq 2$. If the toe distance L is known, then the thickness reduction factor is calculated according to Eq.(8) [2]:

$$f(t) = \left(\frac{t_{ref}}{t} \right)^n \left(\frac{2t}{L} \right)^{0.1} \quad (8)$$

The FAT class of structural detail is multiplied by the values of $f(t)$ to consider the thickness effect. However, in IIW recommendations, due to limited data, the gain in fatigue strength from the thinness effect, when the thickness is below the reference value, is not considered.

In the SSAB design handbook, the correlation between fatigue strength and thickness is described by Eq.(9) [28]:

$$\Delta\sigma = \Delta\sigma_0 \left(\frac{t_0}{t} \right)^n \quad (9)$$

In this formula exponent n varies between 0 to 0.15 depending on the joint category, t_0 is the reference thickness, which is 15 mm, and t is the thickness.

4.4 Angular misalignment

Although studies suggest that reducing thickness can increase fatigue strength, this is not always the case, as geometric and weld defects, such as misalignment [22] and undercuts [29], may have detrimental effects. Misalignment leads to an increasing stress level in the welded joint as a result of secondary bending stress. The misalignment effect is accounted for by applying the stress magnification factor, k_m , which is explained in Eq.(10) [2].

$$k_m = 1 + \lambda \cdot \alpha \cdot \frac{l_1 \cdot l_2}{T \cdot (l_1 + l_2)} \quad (10)$$

In this formula T is the thickness of plates, and since the in-plane displacement of the transverse plate is not restricted, the parameter λ sets to 3. The definition of an angle α and l_1, l_2 and also the variation of α is shown in Fig. 11.

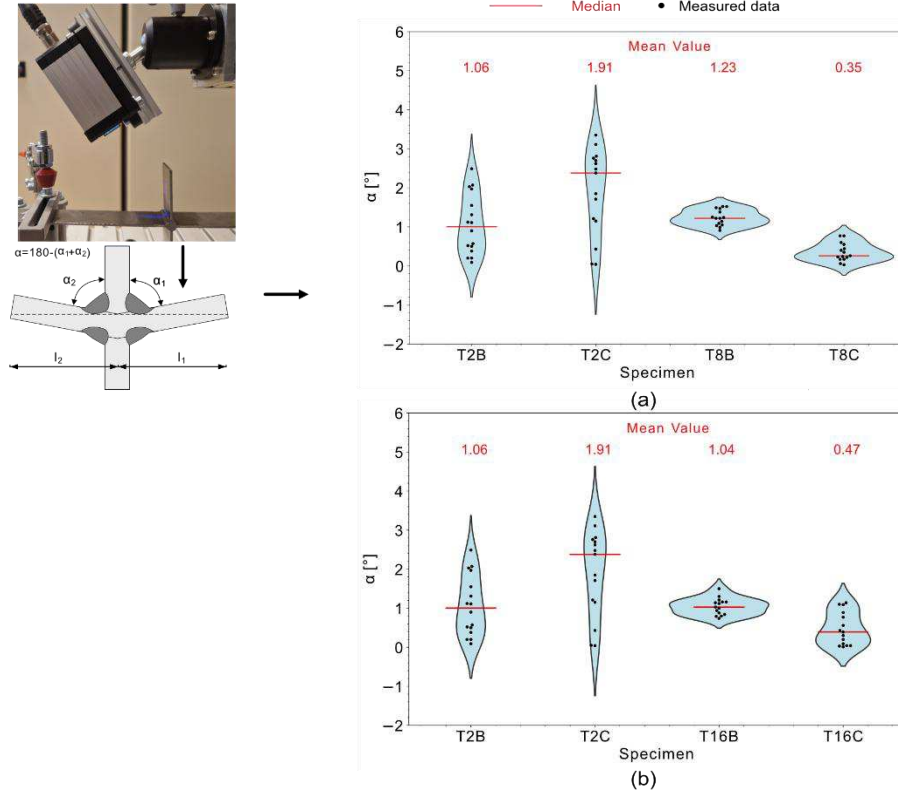


Figure 11: Variation of angular misalignment in thicknesses (a) 2 mm and 8 mm [19], (b) 2 mm and 16 mm [20].

The effective stress magnification factor is calculated by Eq.(11) as follow:

$$k_{m,eff} = \frac{k_{m,calculated}}{k_{m,alreadycovered}} \quad (11)$$

where $k_{m,calculated}$ is obtained from Eq.(10), and $k_{m,alreadycovered}$ is set to 1.2 for transverse non-load-carrying attachment [2].

Fig. 12 presents the stress ranges, including the modified nominal stress with the thickness reduction factor, plotted against plate thicknesses and normalized to the reference thickness [2]. The plot also shows the variation of nominal stress from fatigue tests and the effective notch stress calculated for the specimens analysed in [19].

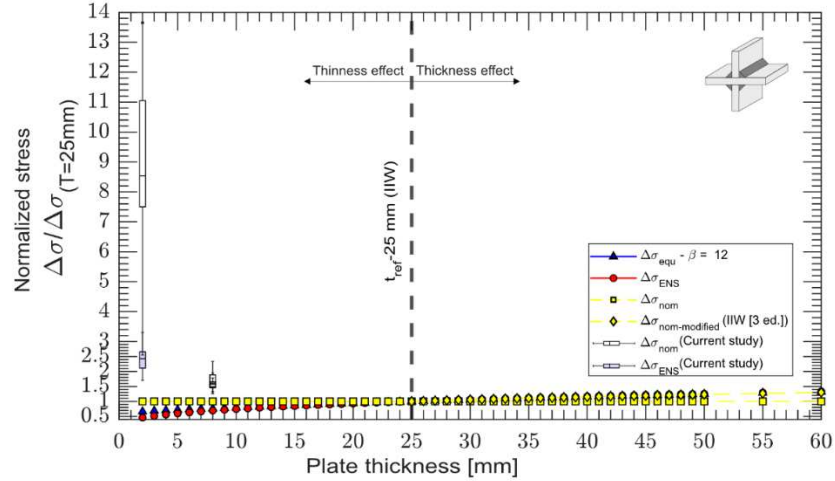
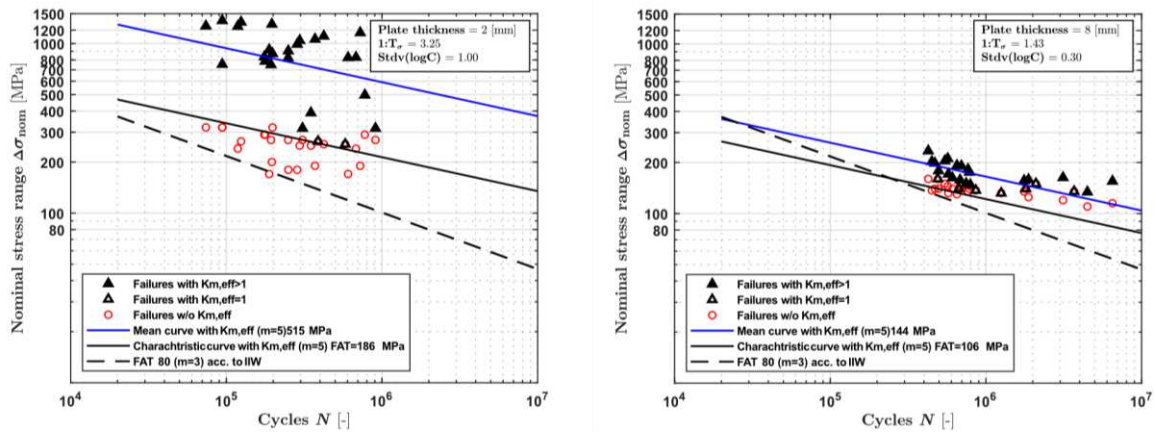
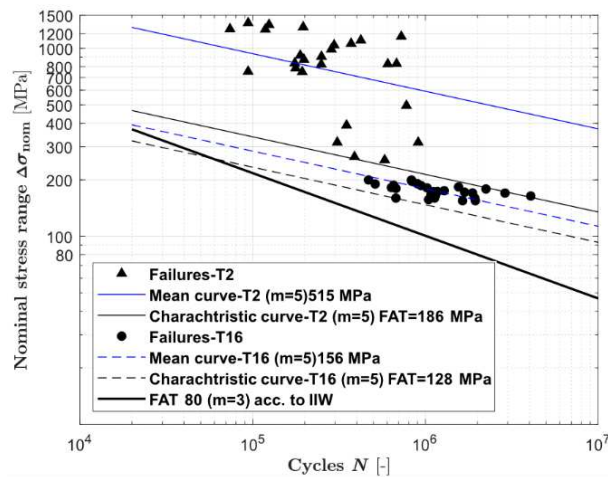


Figure 12: Stress variation for a range of plate thickness [19].

Nominal S-N curves from specimen fatigue tests adjustment using the effective stress magnification factor, are presented in Fig. 13 and Fig. 14. Mean and characteristic curves (slope $m = 5$) fitted to the adjusted results align well with the observed trends.

Figure 13: Nominal stress versus number of cycles to failure (left) $T=2$ mm (Right) $T=8$ mm [19].Figure 14. Nominal stress versus number of cycles to failure $T=2$ mm and $T=16$ mm [20].

Effective notch stress S-N curves are shown in Fig. 15 with a fixed slope of $m = 5$, including data points both with and without explicit modelling of misalignment.

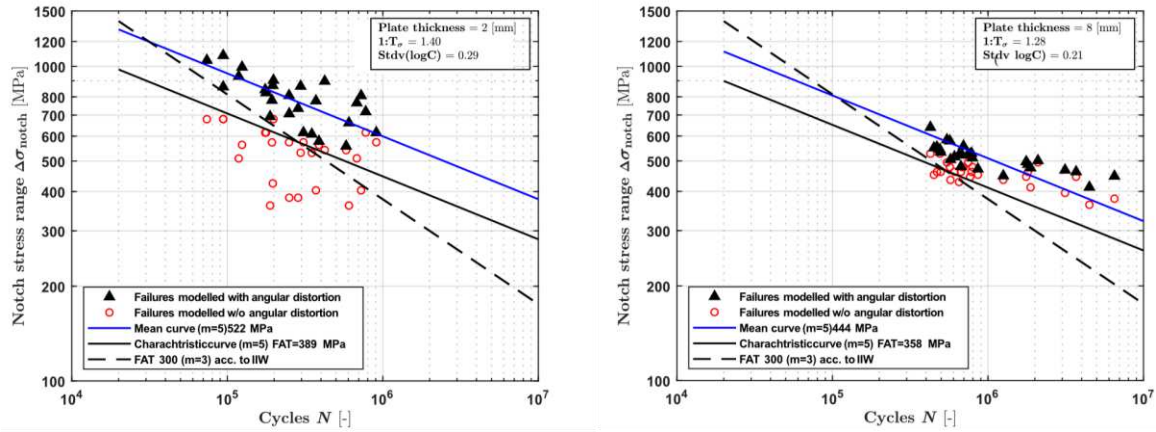


Figure 15: Notch stress versus number of cycles to failure (left) $T=2$ mm (Right) $T=8$ mm [19].

The results indicate that the increase in fatigue strength with decreasing plate thickness reflects the thinness effect. Additionally, accounting for stress due to angular misalignment further enhances fatigue strength, with a more pronounced effect observed in thinner specimens. Mean and characteristic stress ranges for nominal and notch stress for plate thicknesses 2 mm and 8 mm is presented in Tab. 1.

Table 1: Mean and characteristic stress ranges for nominal and notch stress [19].

	Stress range (MPa)	
	T2	T8
$\Delta\sigma_{mean-nom} (P_f = 50\%)$	515	144
$\Delta\sigma_{characteristic-nom} (P_f = 2.3\%)$	186	106
$\Delta\sigma_{mean-notch} (P_f = 50\%)$	522	444
$\Delta\sigma_{characteristic-notch} (P_f = 2.3\%)$	389	358

The influence of weld quality on fatigue strength was evaluated for all test series, as presented in Tab. 2 and Tab. 3. Adjusted results show that lower weld quality reduces fatigue strength due to smaller weld toe radii and angles, which increase stress concentrations. Scatter analysis indicates that higher weld quality decreases variability in fatigue strength, with thinner plates (2 mm) showing greater sensitivity to variations in weld quality.

Table 2: Variation of scatter data without and with adjustment with $K_{m,eff}$ [19].

Specimen	$\Delta\sigma_{mean-nom} (P_f = 50\%)$ [MPa]	$\Delta\sigma_{characteristic-nom} (P_f = 2.3\%)$ [MPa]	$Stdv(LogC)$	$Stdv(LogC) with K_{m,eff}$	$1:T_\sigma$	$1:T_\sigma with K_{m,eff}$
T2B	510	173	0.27	0.91	1.38	2.93
T2C	519	147	0.42	1.10	1.65	3.66
T8B	156	122	0.22	0.21	1.30	1.29
T8C	130	98	0.23	0.23	1.32	1.32

Table 3. Variation of scatter data without and with adjustment with $K_{m,eff}$ [20].

Specimen	$Stdv(LogC)$	$Stdv(LogC)withK_{m,eff}$	T_σ	$T_\sigma withK_{m,eff}$	$\Delta\sigma_{characteristic-nom} (P_f = 2.3\%)$	$\Delta\sigma_{characteristic-nom} (P_f = 2.3\%)withK_{m,eff}$
T2B	0.27	0.91	1.38	2.93	135	173
T2C	0.42	1.10	1.65	3.66	91	147
T16B	0.19	0.20	1.49	1.27	119	125
T16C	0.17	0.19	1.41	1.25	124	124

5. Discussion

Angular misalignment is a key factor reducing the fatigue strength of thin-welded specimens, as it introduces extra bending stresses caused by out-of-plane deformation from weld shrinkage. If misalignment is not included in stress evaluation, fatigue strength may be overestimated. Accurately measuring and incorporating this global geometric imperfection, referred to as the technological size effect, is essential for reliable fatigue assessment of thin-walled welded structures. Statistical results show that angular misalignment decreases as plate thickness increases. In this study, the impact of misalignment is evaluated using an effective stress magnification factor. The results indicate that a fatigue strength exponent of $m = 5$ fits the experimental data better than the conventional value of $m = 3$. This suggests that the high weld quality of the specimens enhances fatigue performance, supporting the use of a higher exponent when evaluating high-quality welded joints.

Weld geometry has a significant impact on fatigue performance. High-resolution laser scanning provides a more effective way to capture weld geometry and study its correlation with fatigue behaviour. As it is shown, lowering weld quality from B to C reduces both the weld toe radius and toe angle for all plate thicknesses.

After adjusting for angular misalignment, the fatigue results remain conservative compared with the IIW FAT80 design curve.

A key observation is that at 2 million cycles (2.3% failure probability), fatigue strength increases as plate thickness decreases, highlighting the thinness effect.

6. Conclusion

The present work explores the size effect and, more specifically, the thinness effect on the fatigue strength of welded specimens with transverse non-load-carrying attachment. To achieve this aim, fatigue testing, finite element analysis and probabilistic modelling considering the weakest link approach have been performed. The following conclusions can be drawn from the results:

- In non-load-carrying welded attachments, the probabilistic method reduces scatter compared to the conventional nominal stress method.
- Probabilistic models can help improve the understanding of the size effect in welds under fatigue loading.
- For thinner thicknesses, fatigue strength evaluation shows improved agreement with experimental results when applying the probabilistic method with a 1 mm radius.
- The quality of welds strongly affected fatigue performance; better-quality welds reduced stress concentrations through larger weld toe radii and weld toe angles, which in turn increased fatigue life.
- A significant thinness effect was identified, where thinner plates demonstrated higher fatigue strength.
- Angular misalignment affected thin-walled welded joints more strongly, generating secondary bending stresses and increasing the stress magnification factor. Accounting for this misalignment led to improved fatigue life predictions.

- Existing design guidelines primarily consider thickness effects on fatigue strength but offer limited guidance for thin plates. The findings of this study indicate that current fatigue design rules may be overly conservative for thin-walled structures.

Data Availability Statement

Data will be made available on request.

Authors Contributions

Mehdi Ghanadi: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - Original Draft. **Zuheir Barsoum:** Conceptualization, Writing - Review & Editing, Supervision, Funding acquisition.

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Competing interest

The authors declare no competing interests.

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