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A systematic review of stress concentration factors (SCFs) in composite reinforced circular hollow section (CHS) joints

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ABSTRACT

"Composites are an emerging choice for strengthening and repairing compromised structures due to their attractive mechanical properties, environmental durability, and ease of application. After decades of successful use as environmental coatings and for strengthening secondary load members, and with advancements in materials and application techniques, composites are increasingly being used for primary load-bearing components, such as the joints of circular hollow section (CHS) members. The structural stress approach is widely used for the fatigue analysis of CHS joints. This approach utilises stress concentration factors (SCFs) in the joint to determine hot-spot stress, which is then used in conjunction with the respective S-N curve for fatigue life estimation. Composite reinforcement of CHS joints is increasingly being investigated to enhance fatigue life. Various studies have reported a positive impact of composite reinforcement on fatigue strength, either directly or by reducing SCFs in CHS joints. However, certain aspects remain unexplored, while others are frequently revisited. The use of composites for reinforcing tubular joints is systematically reviewed following PRISMA guidelines. Twenty-four articles were selected for detailed study after applying various exclusion and inclusion criteria and removing duplicate records, with eleven, five, three, four, and one articles on T/Y, K, KT, X, and TT-joints, respectively. A critical review of these articles shaped the current understanding of the capabilities of composite reinforcement in CHS joints for enhancing fatigue life and identified areas for future research. These gaps include the investigation of composite reinforcement for joints under combined loads, the optimisation of reinforcement layup, and the development of empirical equations for determining SCFs in various joints under different load configurations."

1. Introduction

Circular hollow section (CHS) structures offer high specific strength, stiffness, and direction-independent structural response. CHS structures have widespread applications in civil and offshore structures and are usually subjected to fatigue loads due to the dynamic nature of loads and long service life. Over time, repair or rehabilitation of these structures may be required. Conventional approaches usually involve welding, which causes high concentrations of stress and residual stresses, making the structure prone to failure [1]. On the other hand, composite reinforcement does not introduce stress concentrations and can be applied to any structure without special tooling. The ability of fibre-reinforced polymer (FRP) composites to cure in an aquatic environment widens their application to offshore structures. Composites offer excellent corrosion resistance and durability under extreme environmental conditions and were initially used for environmental protection and reinforcement of non-critical structural members. They were subsequently used to rehabilitate primary load-bearing members.

Several articles have comprehensively reviewed composite material utilisation for repairing steel structures. Teng et al. [2] found that external bonding of composites can improve the fatigue life. Zhao et al.

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List of Abbreviations and symbols

AFRP	Aramid fibre-reinforced polymers (Kevlar)
ANOVA	Analysis of variance
CHS	Circular hollow section
CFRP	Carbon fibre-reinforced polymers
D	Diameter of chord
d	Diameter of brace (all braces kept same)
E_{frp}	Elastic modulus of composite reinforcement
E_{joint}	Elastic modulus of joint material
FE	Finite element
FEA	Finite element analysis
FEM	Finite element method
FRP	Fibre-reinforced polymers
GFRP	Glass fibre-reinforced polymers
HSS	Hot spot stress
IPB	In-plane bending moment
SPSS	Statistical Package for the Social Sciences
OPB	Out-of-plane bending moment
Peak HSS	Maximum hot-spot stress (HSS)
Θ	Angle of the inclined brace with chord axis
T	Thickness of chord
T_{frp}	Thickness of composite reinforcement
T_{chord}	Thickness of the chord
t	Thickness of brace (all braces kept same)
g	Gap between the central and inclined brace
σ_n	Nominal stress
β	d/D
γ	$D/2T$
τ	t/T
α	$2L/D$
ζ	g/D
ϵ	E_{frp}/E_{joint}
η	T_{frp}/T_{chord}
ψ	SCF reduction coefficient
ZPSS	Zero Point Structural Stress

[3] reviewed the FRP reinforcement of hollow section members made of steel and the propagation of fatigue cracks in FRR-reinforced steel structures. It was concluded that composites have great potential for retrofitting steel structures. Gholami et al. [4] reviewed studies on CFRP strengthening of steel structures, focusing on the effect of environmental conditions, and concluded that the impact of exposure must be investigated to determine the actual behaviour of the strengthening system. Lim et al. [5] reviewed the repair of pipelines using composite, discussing the advantages and limitations of pre-cured layered, flexible wet layup, pre-impregnated, split composite sleeve, and flexible tape systems. Karbhari [6] compiled data on the rehabilitation of pipelines using composites. These references provide an understanding of the capacity of composites to reinforce critical structures. However, these studies are limited to simple structures, such as plates, beams, and pipes, and do not apply to complex structural members, such as the joints of CHS structures.

The tubular joint, which is the interface of two or more CHS members, is the most critical part of a tubular structure. The common types of tubular joints are shown in Fig. 1 [7]. Stresses at the interface are amplified due to the weld notch and the complex geometry of the joint, as shown in Fig. 2 [8]. The weld toe of these joints is critical, as it is susceptible to fatigue crack initiation. Cracks at the weld toe of joints are more prone to propagate than in other locations of the structure. These cracks can grow and cause catastrophic failure. The repair or strengthening of such joints is essential to retain structural integrity. Such operations may also be required to enhance the lifespan of a tubular structure, especially when facilities operate beyond their design life. Reinforcing critical structural members, including joints, may be necessary to meet revised design codes or legislation with more stringent requirements.

The first use of composite reinforcement for tubular joints was by Pantelides et al. [9]. Since then, numerous studies have investigated the composite reinforcement of various tubular joints. Prashob et al. [10] reviewed techniques for strengthening steel and concrete structures, including a limited discussion on the reinforcement of tubular joints with composites. Iqbal et al. [11] recently reviewed techniques used to reinforce tubular joints. A comprehensive summary of methods for composite reinforcement of tubular joints was reviewed, including off-the-shelf products. Although composite reinforcement was identified as a viable alternative to other approaches, it was not an engineering

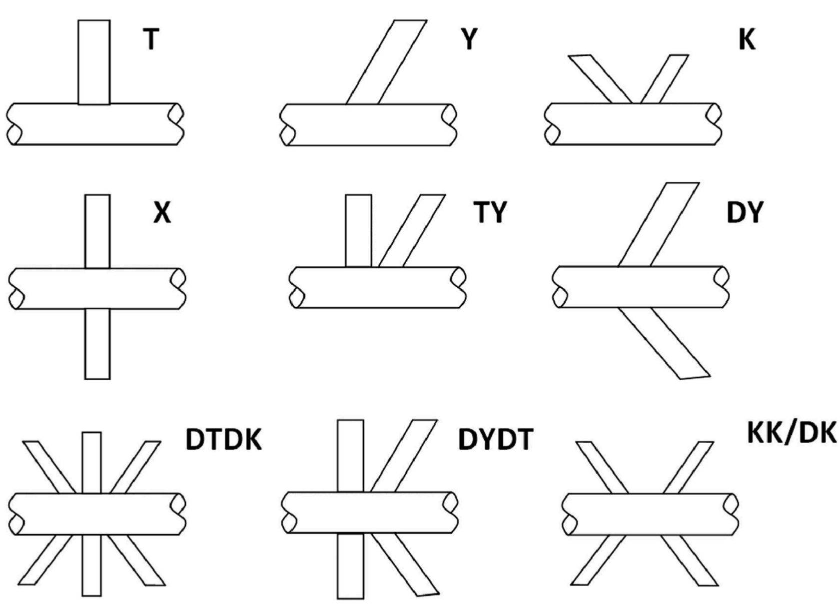

Fig. 1. Typical tubular joints in offshore structures [7].

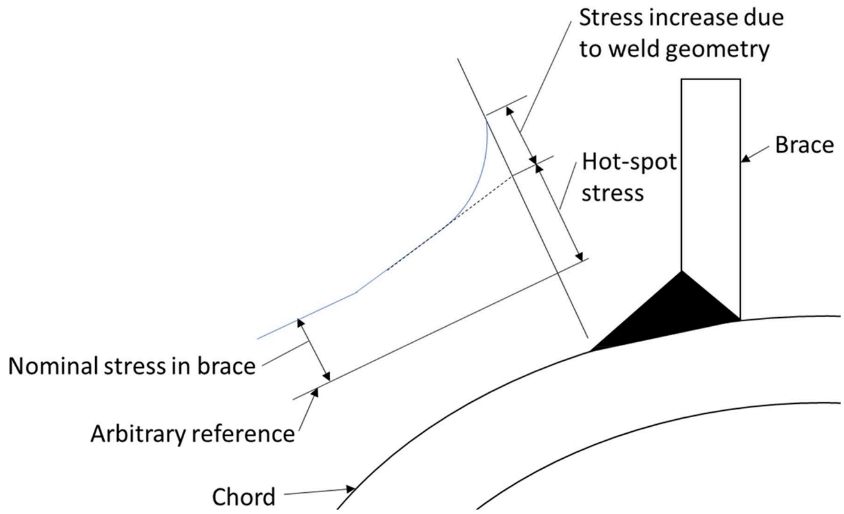

Fig. 2. Stress behaviour at the joint [8].

analysis of composite reinforcement. An engineering analysis on composite reinforcement of CHS is still unavailable.

Numerous researchers have investigated CHS joints reinforced with composites and their loading conditions to enhance ultimate load capacity and reduce stress concentration factor (SCF). Some have developed parametric equations for determining SCF or approximating SCF behaviour with probability distribution functions. Parametric studies and sensitivity analysis were also performed to explore the effect of various geometric and reinforcement variables on SCF. This review aims to consolidate existing work on composite reinforcement of load-bearing tubular joints for enhancing fatigue strength, following PRISMA guidelines for systematic reviews. While traditional reviews can be subjective [12], a systematic literature review is a transparent scientific process that aims to reduce the authors' biases and omissions and can be repeated for verification. The term 'systematic' refers to the specific research question, search strategy, and inclusion and exclusion criteria and is widely used for the reviews and procedures of synthesising the findings. This process will always result in similar findings independent of the reviewer.

2. Methodology

The PRISMA-2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines were followed in this study [13]. PRISMA protocol consists of a 27-item checklist to enhance reliability and transparency. The PRISMA protocol was adopted because of its comprehensiveness, author-independent outcomes, and acceptability across scholars.

The critical search databases were identified through a search in Google Scholar using random keywords. A comprehensive literature search on composite reinforcement of CHS joints was performed through Web of Science (WoS), Scopus, and Google Scholar. All search results were documented to ensure repeatability and transparency. A search protocol was carried out in titles and abstracts comprising the following keywords and inclusion/exclusion criteria: (*strengthen* OR *reinforce* OR *rehabilitat* OR repair OR *retrofit* OR *wrap* OR *stiff*) AND (composite* OR *FRP* OR *fiber* OR *fibre* OR CFRP* OR GFRP* OR AFRP* OR BFRP*) AND ((*tubular* OR *CHS* OR *circular*) AND *joint*) AND NOT (RHS OR SHS OR rectangular* OR square* OR concrete OR beam). For searches in the Web of Science (WoS) database, the following keywords and inclusion/exclusion criteria were used: AB= ((strengthen OR reinforce OR rehabilitat OR repair OR retrofit OR wrap OR stiff) AND (composite OR FRP OR fiber OR fibre OR CFRP OR GFRP OR AFRP OR BFRP) AND (tubular OR CHS OR circular) AND joint). All papers published till the end of 2023 were considered. Articles related to computer science, chemistry, physics and astronomy, chemical engineering, health professions, biochemistry, genetics, and molecular biology were excluded.

The article title, journal name, year of publication, authors' names, affiliations, abstract, and keywords of the shortlisted records were exported to a Microsoft Excel spreadsheet. This data was screened, and abstracts were read thoroughly to extract information such as the investigation approach, the development of empirical models, and the software tool used. Articles related to square hollow sections and rectangular hollow sections were excluded, as the physics of these joints is different from CHS joints. These two shortlists were merged, and duplicate records were deleted. Two individuals conducted this process independently, and articles unrelated to the objective were discarded. The final list was analysed in detail and presented in the following section.

Frequently reported geometric parameters are defined prior to proceeding with further discussion to establish a foundation. These include the ratio of the brace diameter to the chord diameter (β), ratio of chord diameter to twice its thickness (γ), ratio of twice length to chord diameter (α), ratio of the circumferential gap to the chord diameter (ζ), ratio of brace thickness to chord thickness (τ), and angle between brace and chord axis (Θ). The common reinforcement parameters are the elastic modulus, layer thickness, number of layers, and reinforcement orientation. The elastic modulus is usually expressed as the ratio of the elastic modulus of reinforcement to the elastic modulus of the joint (€), whereas the thickness of reinforcement as the ratio of reinforcement thickness to the chord thickness (η). Some of these symbols are interchangeably used. These parameters are illustrated in Fig. 3 for a typical KT-joint. The crown and saddle points are also shown in cross-section A-A of Fig. 3.

3. Results and discussion

The initial abstract search through Scopus resulted in 274 articles. After excluding articles in press, conference proceedings, thesis, and those written in languages other than English and including articles in the engineering discipline only, 114 articles were shortlisted. Articles unrelated to the objective were dropped using the exclusion and inclusion criteria, and eighty-nine articles were selected for further analysis. The initial search through the WoS resulted in 207 articles. This list reduced to 122 articles in English and those related to engineering. This list was merged with eighty-nine articles from Scopus, and a comprehensive list of 211 articles was obtained. After removing duplicates, 180

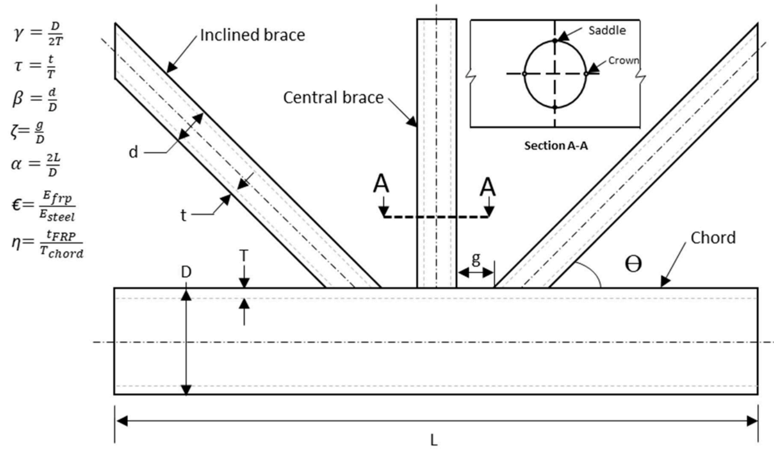

Fig. 3. A typical CHS KT joint.

articles remained, which were studied critically. Out of these, only twenty-four relevant articles were investigated, establishing the state of the art in composite reinforcement of tubular joints and directions for future research.

The use of composite for reinforcing CHS joints initiated with its utilisation for enhancement of static strength or static load capacity, with the pioneering study by Pantelides et al. [9] in 2003, who determined the recovery of the static load-bearing capacity of cracked aluminium K-joints of overhead sign structures using GFRP reinforcement. This study opened a wide avenue for research on the utilisation of composites for the repair of CHS joints. Subsequently, Fam et al. [14] 2006 investigated the use of CFRP and GFRP for reinforcement and observed more strength recovery with CFRP for K-joints under axial tension. Following these, many other researchers also investigated the load capacity of composite reinforced joints, such as Chen et al. [15], Lesani et al. [16–18], Fu et al. [19], and Prashob et al. [20]. However, these studies were not related to fatigue life enhancement; hence, these articles were discarded. Similarly, investigation on local joint flexibility (LJF) of T/Y joints by Nassiraei et al. [21] and bulking load capacity of T-joints by Alembagheri et al. [22] and Yazdi et al. [23] were also not covered in this review.

A list of twenty-four articles was selected for final review after screening each record based on their titles and abstracts. These articles were published as recently as 2023, while the first article on composite reinforcement of CHS joints related to fatigue life was published in 2007. Full papers were downloaded for these twenty-one records and were analysed in detail. All the selected articles were critically studied and distributed in two broad categories: direct fatigue life investigation and SCF. These are discussed in the following sections:

3.1. Fatigue strength of composite reinforced CHS joints

Four articles were found that investigated the fatigue strength of composite-reinforced CHS joints, as listed in Table 1. All these studies were based on experimental testing of composite reinforced joints. The first study was by Nadauld and Pantelides [24], published in 2007. They carried out constant amplitude fatigue testing of aluminium-made K-joints of overhead sign structures using joints with cracks and reinforced with GFRP. This was the first study to focus on fatigue life enhancement using composite reinforcement. 90 % of the joint weld was removed, repaired with GFRP, and then tested. It was reported that the fatigue strength of reinforced joints was greater than that of the actual joint. The joint with 90 % weld removed and then reinforced with GFRP exhibited 90 % of the fatigue threshold.

Table 1
List of literature on fatigue strength of composite reinforced CHS joints.

S. No.	Reference	Year	Joint type	Finding(s)
1	Nadauld et al. [24]	2007	K	The fatigue strength of a joint with a defective interface weld was regained.
2	Deng et al. [25]	2020	T/Y	Improved energy dissipation and ductility index were achieved.
3	Tong et al. [26]	2021	K	An enhancement of 138 % was achieved in the fatigue strength.
4	Xu et al. [27]	2022	TT	An increase of 47 % was observed in the fatigue strength.

The second study was by Deng et al. [25], who investigated the effect of composite reinforcement on CHS T/Y-joints. Four joints were tested under cyclic load. The CFRP-reinforced joint exhibited a higher ductility index when subjected to tension and compression cyclic loads. Similarly, Tong et al. [26] investigated the fatigue strength of composite-reinforced K-joints. Eight CFRP-reinforced and three unreinforced K-joints were tested under cyclic loading. An average increase of 138 % was observed for reinforced joints. An S-N curve was also proposed for CFRP-reinforced CHS K-joints. The most recent study that investigated the fatigue strength of composite-reinforced CHS joints was Xu et al. [27]. They investigated CFRP-reinforced TT-joints under cyclic axial load. An increase of 47 % was observed in fatigue life due to a specific CFRP reinforcement of TT-joint. This study also covers composite reinforcement's effect on SCF, which will be discussed later in the respective section.

These studies provide a theoretical understanding of the capability of composite reinforced to improve fatigue strength. However, more investigation is required for the practical implementation of composite reinforcement. The modified S-N curve by Tong et al. [26] could be used for the estimation of future life for CFRP-reinforced K-joints. However, similar curves are still unavailable for other types of CHS joints and loading conditions. These studies were essentially experimental, which are mostly expensive and take substantial time.

On the other hand, various researchers have investigated the structural hot-spot stress (HSS) approach, focusing primarily on the SCF in composite reinforced joints. The determined SCF for a composite reinforced CHS joint can be used to calculate HSS, which is used in conjunction with its respective S-N curve to estimate the fatigue strength. This approach is relatively straightforward and widely used in the design stage [28]. The rest of the 21 articles identified in the systemic literature search were related to SCF, which are discussed in the following section.

3.2. Stress concentration factors in composite reinforced CHS joints

Most studies on the composite reinforcement of CHS joints for enhancing fatigue strength have focused on the reduction in SCF through composite reinforcement. Seventeen articles were found on this objective, with the first article by Hosseini et al. [29] in 2019. Since then, in a substantially short period of time, various others have also published their research on this topic. These articles have been critically analysed and presented in chronological order in Table 2. This table presents a summary of these articles and their significant findings, to assess what aspect of composite reinforcement was investigated and their findings relating to the reduction of SCF in CHS joints.

3.2.1. T-joint

Hosseini et al. [29] investigated the reduction of SCF in FRP-reinforced T-joints under IPB and OPB using 150 simulations through ABAQUS software. This was the first study investigating the use of FRP reinforcement to reduce SCF, reporting a significant decrease in SCF in composite reinforced joints, with CFRP being more effective than GFRP. A parametric study was also carried out, revealing the thickness and elastic modulus as the most critical factors for SCF reduction, while the reinforcement length had a negligible effect on SCF. An efficient layup for the T-joints under IPB and OPB load was also identified, i.e., orienting reinforcement along the chord axis for IPB and in the hoop direction of the chord for OPB. A similar study by Hosseini et al. [30] found SCF reduction with FRP reinforcement of T-joint under axial load, IPB, and OPB. The axial load case was considered for the first time, while the other loadings were similar to their previous work Hosseini et al. [29]. Based on a parametric study, the optimal orientation was found to be the hoop direction of the chord for axial load on T-joints. The SCF reduction effect of composite reinforcement was found to enhance with an increase in the mechanical properties of reinforcement.

Table 2
List of articles on SCF in composite reinforced CHS joints.

S. No.	Reference	Year	Joint type	Load type/ direction	Nature of investigation
1	Hosseini et al. [29]	2019	T/Y	IPB, OPB	Numerical
2	Hosseini et al. [30]	2019	T/Y	Axial compression, IPB, OPB	Numerical and experimental
3	Tong et al. [31]	2019	K	Balanced axial load	Experimental
4	Xu et al. [32]	2020	K	Balance axial load	Numerical and experimental
5	Hosseini et al. [33]	2020	T/Y	Axial compression	Numerical and experimental
6	Nassirian et al. [34]	2020	T/Y	Axial compression	Numerical
7	Nassiraei et al. [35]	2020	T/Y	IPB	Numerical
8	Hosseini et al. [36]	2020	T/Y	Axial compression	Numerical
9	Nassiraei et al. [37]	2021	T/Y	OPB	Numerical
10	Hosseini et al. [38]	2021	KT	Axial loads on all braces	Numerical
11	Nassiraei et al. [39]	2021	X	Axial compression	Numerical
12	Nassiraei et al. [40]	2021	X	OPB	Numerical
13	Nassiraei et al. [41]	2021	X	IPB	Numerical
14	Zavvar et al. [42]				
	2021	KT	IPB, OPB on all braces	Numerical	
15	Nassiraei et al. [43]	2021	T/Y	Axial compression, IPB, OPB	Numerical
16	Nassiraei et al. [44]	2022	X	Axial compression, IPB, OPB	Numerical
17	Xu et al. [27]	2022	TT	Axial tension	Numerical and experimental
18	Mohamed et al. [45]	2022	K	Balance axial load	Numerical
19	Mohamed et al. [46]	2022	T/Y	Axial compression	Numerical
20	Hosseini et al. [47]	2022	T/Y	IPB, OPB	Numerical and experimental
21	Zavvar et al. [48]	2023	DKT	Axial loads on all braces	Numerical

These studies were further extended by Hosseini et al. [33] through experimental and numerical investigations on the SCF T-joint under axial compression load. It was found that the SCF reduction is achieved mainly by FRP reinforcement on the chord member rather than the brace. The parametric study reported that increasing β, τ, γ, and elastic modulus and thickness of reinforcement enhanced the SCF reduction effect of composite reinforcement. A novel parametric equation was also proposed for determining SCF at the crown position of an FRP-reinforced T-joint under brace axial compressive load. Similar findings were restated by Hosseini et al. [36] also.

Another research group also contributed significantly to the investigation of composite reinforced T/Y-joints. Nassiraei and Rezadoost [34] investigated the effect of composite reinforcement on SCF in T/Y-joints subjected to axial compressive load. The difference between this study and Hosseini et al. [30,33] was that here the angle between brace and chord was defined as a variable instead of a fixed 90° between brace and chord; hence, both T and Y-joint configurations were covered. 134 simulations were carried out using ANSYS, and up to 34 % reduction in SCF was reported. Two parametric formulas were proposed based on regression analysis through SPSS software. These models could be used for SCF at crown and saddle points of composite reinforced T/Y-joints. However, these models were developed by simulating a single reinforcement material (unidirectional GFRP with an elastic modulus of 38.6 GPa in the fibre direction) and hence are only applicable for a similar layup with 4–12 layers, as mentioned in that article. In addition, Nassiraei and Rezadoost [35] investigated T/Y-joints under IPB load and reported up to 40 % reduction in SCF. Using SPSS regression analysis of simulations results generated through 134 FE models, with and without FRP, simulated using ANSYS, two parametric equations were proposed for SCF at the toe and heel positions of T/Y-joints.

A further study by Nassiraei and Rezadoost [37] investigated the OPB-loaded T/Y-joint reinforced with various FRP materials (GFRP, CFRP, AFRP). 263 FE models were simulated through ANSYS. It was inferred that the reduction in SCF is directly proportional to the thickness and elastic modulus of reinforcement material. A parametric equation was proposed to determine SCF at the saddle point of the T/Y-joints under OPB. This equation includes the thickness and modulus of reinforcement material as variables. A parametric study was also covered, similar to Hosseini et al. [29,30]. Research on this topic was extended in Nassiraei and Rezadoost [43] investigating the probability distribution of SCF in FRP-reinforced T/Y-joints under axial, IPB, and OPB. 284 FE models were simulated to generate data for evaluating the goodness-of-fit through Chi-squared and Kolmogorov-Smirnov tests and concluded that Weibull distribution offers the best fit for axial while Gamma distribution for IPB and OPB.

While the conventional structural stress approach utilises surface stress for determining the HSS, which is further used to estimate the fatigue strength of CHS joints through respective S-N curves, Mohamed et al. [46] investigated SCF reduction due to CFRP reinforcement of T/Y-joints under axial compression using the Zero Point Structural Stress (ZPSS) approach, owing to the more realistic determination of HSS by incorporating the effect of bending stresses in HSS. 132 FE models were simulated in ABAQUS to develop an equation for determining SCF at the saddle point of CFRP-reinforced T/Y-joints under axial compression loads. It was reported that SCF reduced with an increase in the number of reinforcement layers, whereas the effect of reinforcement, i.e. the sensitivity of SCF reduction diminished with an increase in the number of reinforcement layers. The impact of reinforcement increased with a rise in the brace inclination angle, β and γ, while decreased with an increase of τ. A parametric equation was also proposed for determining SCF at the saddle point. Besides using the ZPSS approach for determining SCF, this study's results were similar to previous studies that used surface stress extrapolation.

Hosseini et al. [47] investigated SCF in composite reinforced T/Y-joints under IPB and OPB. This study proposed empirical equations for determining SCF at the crown for a T/Y-joint under IPB and saddle under OPB. A significant reduction in SCF was achieved using composite reinforcement. While the empirical model for OPB was previously presented by Nassiraei et al. [37], a model for T/Y-joint under IPB was investigated for the first time. The contact between reinforcement and joint was also assessed for the first time. It was reported that the effectiveness of reinforcement increases with elastic modulus, number of reinforcement layers, and γ, and decreases with an increase in β, with negligible change for τ. It was also found that reinforcement is more effective for joints having a brace at a right angle or close to a right angle.

In summary, eight articles were found on SCF in CHS T-joints. It was found that SCF can be substantially reduced through composite reinforcement and parametric equations were proposed for determining SCF in composite reinforced T/Y-joints at saddle and crown points.

3.2.2. K-joints

Tong et al. [31] tested CFRP-reinforced K-joints under balanced axial loads (tension load on one brace and compression on the other). A 15–20 % reduction in SCF was reported for joint reinforced with specific CFRP material and layup. It was found that the HSS consists of membrane and bending stress. The concept of the SCF reduction coefficient (ψ) was novel. Once the reduction coefficients are determined, the existing equations for SCF and DoB and S-N curves can be applied to estimate fatigue strength. Theoretical formulas were proposed for determining the SCF reduction coefficient. It was also revealed that the SCF reduction coefficient increases with an increase in the thickness of chords, γ and the number of reinforcement layers, while the effect of β was negligible. This study was extended by Xu et al. [32], who developed an empirical model through regression analysis of simulation data obtained from 1011 simulations through ABAQUS for determining coefficient ψ at specific positions of K-joints under balanced axial load. An extended parametric study found that the SCF reduction coefficient (ψ) depends on the thickness and elastic modulus of reinforcement and the elastic modulus of adhesive. The effect of γ, β, *and*Θ(brace inclination angle) was minimal, while an increase in adhesive layer stiffness increased SCF.

While Tong et al. [31] emphasised the inclusion of bending stresses in HSS through DOB, Mohamed et al. [45] used the ZPSS approach to investigate SCFs in CFRP-reinforced K-joints. Three empirical equations were proposed for determining SCF at the CFRP-reinforced K-joint's heel, saddle, and crown. These equations were developed through regression analysis of the data obtained from 319 FE models in ABAQUS. The effect of composite reinforcement was pronounced with an increase in the number of layers and elastic modulus. Orientating reinforcement along the chord axis was optimal for reducing SCF at the crown, while optimal orientation was orthogonal for the saddle point. The influence of reinforcement was enhanced with an increase of γ, θ (brace inclination), while the effect of τ was negligible. ZPSS approach was emphsied as it incorporates the through-thickness variation of stress in addition to surface stress.

3.2.3. KT-joints

Hosseini et al. [38] investigated KT-joints under three configurations of brace axial loadings using 1458 FE simulations through ABAQUS. This was the first study investigating the composite reinforcement of KT-joints. A parametric study was carried out, but the results were similar to those of Hosseini et al. [29-33] for T/Y-joints. It was reported that the SCF reduces with increasing brace inclination angle (θ) and increases with a rise in γ and τ. The effect of various GFRP and CFRP reinforcements on SCF at the specific positions of KT-joints was studied, and empirical models were developed. This study proposed thirty-eight parametric equations for determining SCF at crown, saddle, heel, and toe of KT-joints subjected to axial load on all braces.

Since this study covered various axial load configurations, Zavvar et al. [42] further investigated the composite reinforced KT-joints under bending load. Composite reinforced KT-joints under IBP and OPB by simulating 2920 FE models in ABAQUS. Thirty-eight parametric equations for determining SCF at crown, saddle, heel, and toe of KT-joints subjected to IPB or OPB load on all braces. These parametric equations for determining SCF at the crown for IPB and saddle for OPB in FRP-reinforced and unreinforced KT-joint were a significant contribution. A sensitivity analysis was conducted for KT-joints under IPB and OPB. When subjected to IPB, it was found that increased thickness and elastic modulus enhanced the effect of composite reinforcement. Similarly, the effect was more pronounced for high β and γ, while the impact of τ depended on the type of loading. On the other hand, for the KT-joints under OPB, the effect of reinforcement thickness and elastic modulus was similar. However, the impact of β and τ was small. The SCF was affected by brace inclination angle when subjected to IPB but was not affected significantly under OPB.

Another joint type, DKT reinforced with various FRP materials and subjected to various axial loads, was investigated by Zavvar et al. [48]. Equations were proposed to determine SCF for joints under different configurations of axial loads. The parametric investigations concluded that SCF is substantially reduced with composite reinforcement. The reinforcement effect is enhanced with increased thickness, number of layers, and reinforcement stiffness, β, γ, and τ.

In summary, KT-joints under various axial, IPB, and OPB load configurations were investigated, and parametric equations are available to determine SCF at the saddle and crown positions.

3.2.4. X-joints

Nassiraei and Rezadoost [39] explored the effect of FRP reinforcement of CHS X-connection under axial loads on SCF through 279 FE models. It was inferred that the FRP reinforcement caused a considerable drop in SCFs and this drop rose with an increase in the number of FRP sheets. The simulation data was used to propose empirical equations for determining SCFs at the saddle and crown points of FRP-reinforced X-joints. This was the first investigation that focused on FRP reinforcement of the X-joints, and a unique parametric equation was proposed for determining SCF at the saddle. Similarly, Nassiraei and Rezadoost [40] investigated SCF reduction in X-joints under OPB. A 23 % reduction in SCF was observed for certain CFRP layups. A parametric study was also carried out; however, the findings of the parametric study were identical to those of previous studies for other joints. It was reported that increasing the number of reinforcement layers and elastic modulus enhances the reinforcement effect, i.e., a more significant drop in SCF. A similar study was also conducted for X-joints under IPB reported in reference [41]. Up to 37 % reduction in SCF was reported, and an empirical equation was proposed for determining SCF in composite reinforced X-joints under IPB. This equation was developed through the regression analysis of the 276 simulations carried out in ANSYS.

While the empirical models for SCF are usually developed through regression analysis of the simulation data, various probability functions have also been investigated to approximate the behaviour of SCF. Nassiraei et al. [44] investigated the probability distribution of the maximum SCF in composite reinforced X-joints under axial, IPB, and OPB. Log-normal distribution was the best approximation for axial loading, while Log-logistic and Generalised extreme value distributions were better for IPB and OPB, respectively. A parametric sensitivity analysis was also carried out, similar to previous studies.

3.3. TT-joints

Xu et al. [27] investigated CFRP-reinforced TT-joints under static and cyclic axial load. 704 FE models were simulated, and the generated data was used to develop empirical models for determining SCF at the crown and saddle. A decrease of 14 % in SCF was observed due to a specific CFRP reinforcement of TT-joint. A TT-joint was also tested under fatigue load, and the S–N curve method was verified for determining fatigue life. A parametric study was carried out to investigate the effect of various parameters on SCF. It was found that SCF reduces with an increased number of reinforcement layers, β and γ, and chord thickness. It was minimally affected by τ.

4. Summary and future directions

Various researchers have investigated the composite reinforcement of CHS joints for the enhancement of fatigue life. Some findings were consistent for a particular joint and load type, while many joints and load cases are still unexplored. This highlights the need for a critical evaluation of the literature to identify future research areas. Several types of CHS joints are used in tubular structures, as shown in Fig. 1. Most studies on composite reinforcement of tubular joints are for T/Y and K-joints, with other complex joints yet to be explored, as listed in Tables 1 and 2.

SCF is a critical parameter in fatigue strength estimation through the structural stress approach. Fig. 4 summarises the articles reviewed and identifies unexplored joints and loadings. Similar investigations for all joints and correlating these findings are vital for building a comprehensive understanding of the behaviour of these joints under various loadings.

Numerous studies have investigated the sensitivity of various input parameters on SCF. Most of these independent variables had similar effects in all studies, indicating that they are independent of joint type. Some input parameters were related to the joint's geometry, while others defined the composite reinforcement. Frequently assessed parameters were α, β, γ, τ, Θ, €, and η, as defined in Fig. 4. The area of joint reinforcement, referred to as the length of reinforcement in some studies, has also been investigated in numerous studies [29,36].

The effect of joint geometry as a function of dimensionless parameters α, β, γ, τ, and Θ in numerous studies appears inconclusive. Notwithstanding this, these seem to have little practical use. Nevertheless, a summary is presented here. Some studies found that the reinforcement effect enhanced with increasing β [36,42,46,48], while some mentioned a decrease [47]. Others reported that its effect was negligible [31,32]. A similar contradiction was found for γ also. It was reported that with an increase of γ the effect of reinforcement increases [27,42,45–48], decreases [31,33,38,41], or remains unchanged [32]. The impact of an increase in τ was found to reduce the reinforcement effect [31–33,38,46,48], while some found this impact to be negligible [27,45,47], and others found it to be dependent on the load type [42]. The effect of Θhas been found to positively affect the reinforcement [38,45,46], while some studies reported it negligible [32]. A study found that the impact of Θ is significant to joint under IPB while it has no effect for OPB [42].

The mechanical properties of the reinforcement, primarily the elastic modulus, positively affects the reinforcement of joints [29,30,33,36,37,40,42,45,47,48]. A higher reinforcement effect was achieved for materials with higher elastic properties, such as CFRP, which performed better than GFRP. The next significant parameter was the reinforcement thickness or the number of layers of reinforcement. The reinforcement effect is enhanced with an increase in the number of reinforcement layers and thickness, while the sensitivity of this effect decreases with an increase in the number of layers applied. [27,29,31,36–38,40,45–48].

An increase in the mechanical properties and reinforcement layer thickness is valid for all joints, loads, and reinforcement materials. However, quantifying the effects of these parameters, such as the mechanical properties of reinforcement material or the optimal reinforcement thickness, is important. Since the mechanical properties of composites widely depend on the fabrication and cure process parameters, workmanship, and the weave architecture of fibre, a generalised conclusion must be devised based on mechanical properties. The strength of reinforcement materials governs the static load capacity of the joint (joint ultimate strength), while the joint's SCF, deflection, and stiffness depend on the stiffness modulus. The lamina strength and stiffness are more important than the fibre type. Therefore, reinforcement properties should be included in the empirical equation, e.g., the stiffness ratio, as used in the empirical models for determining SCF in ref [38,42].

The effect of efficient layup was investigated in many studies. Some studies compared specific layups, while others studied the effect of orientation of reinforcement [29,30,45,47]. The optimum orientation was dependent upon the joint type and load case. Further research is required to investigate the optimal layups of various joints and load cases to develop a generalised understanding of the optimal orientation and stacking sequence. Awareness about the optimal orientation for any joint and load configuration will be of great practical significance [49].

Numerous empirical models have been proposed for the rapid estimation of the effect of composite reinforcement. However, these empirical models are specific to the joint type, load direction, reinforcement material, and layup tested or simulated for data generation used to develop these models. Empirical models that can estimate the effect of composite reinforcement are required for many frequently used joints and load cases, as presented in Table 3. The response of various joints reinforced with composites under numerous loads could also be investigated. Once a database of empirical models for all joints and load types is available, a code/software with a simplified graphic user interface can be developed. This will be incredibly beneficial for quick and efficient estimation of the effect of composite reinforcement.

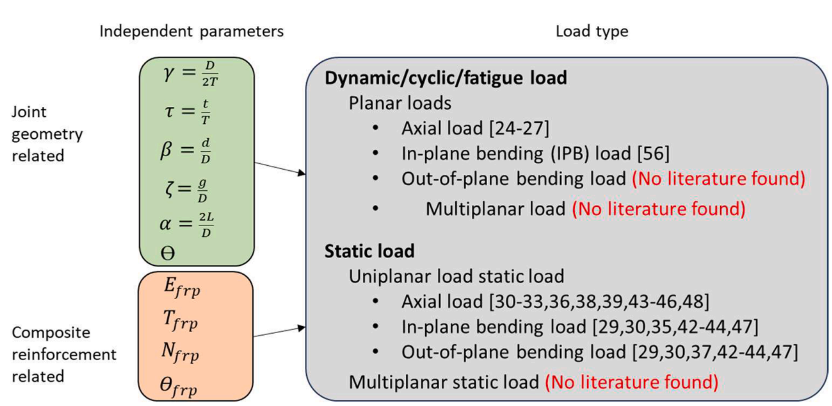

Fig. 4. Unexplored avenues based on the load applied to a composite reinforced CHS joint.

Table 3
Identification of the gap related to the empirical models used in the design and analysis of CHS joints.

Joint type	Axial load	In-plane bending (IPB) load	Out-of-plane bending OPB
T/Y	SCF at saddle: Hosseini et al. [33] Mohamed et al. [46] Probability distribution function for SCF: Nassiraei et al. [43]	SCF at crown: Hosseini et al. [47] SCF at crown and saddle: Nassiraei et al. [35] Probability distribution function for SCF: Nassiraei et al. [43]	SCF at saddle: Nassiraei et al. [37] Hosseini et al. [47] Probability distribution function for SCF: Nassiraei et al. [43]
K	SCF at crown, heel, and saddle: Xu et al. [32] Mohamed et al. [45]		
X	SCF at crown and saddle: Nassiraei et al. [39] Probability distribution function for SCF at saddle and crown: Nassiraei et al. [44]	SCF at saddle: Nassiraei et al. [41] Probability distribution of SCF at crown: Nassiraei et al. [44]	SCF at saddle: Nassiraei et al. [40] Probability distribution function for SCF at saddle: Nassiraei et al. [44]
KT	SCF at crown, saddle, heel, and toe: Hosseini et al. [38] DKT: Zavvar et al. [48]	SCF at crown, saddle, heel, and toe: Zavvar et al. [42]	SCF at crown, saddle, heel, and toe: Zavvar et al. [42]
TT	SCF at crown and saddle: Xu et al. [27]		

Most studies considered axial loads on the brace, followed by OPB and IPB, as listed in Table 2. None of these studies focused on FRP reinforcement of CHS joints under combined loads, even though most practical joints experience combined loads. However, considering the combined load case is complex. Alternatively, the HSS of uniplanar load components can be superimposed to find the combined effect of simultaneous loads [52]. This would require HSS to be determined at more than a single point. All empirical models proposed for estimating SCF or SCF reduction apply to the crown position of composite reinforced CHS joint under IPB and saddle position for joint under axial and OPB, as listed in Table 3. SCF at these specific locations can be substantially lower than the maximum SCF (and the corresponding HSS) when the joint is subjected to multiplanar/complex loading [50,51]. The parametric equation must be able to determine SCF at any point along the chord-brace interface to determine the maximum SCF accurately in such load cases. Gulati et al. [51] recommended determining SCF at eight equally spaced points at the chord-brace interface. Iqbal et al. [28,52,53] proposed SCF determination at 24 equally spaced locations at the chord-brace interface, resulting in a near-exact approximation of maximum SCF and HSS. Recently, Rasul et al. [54,55] proposed some models for estimating SCF in T-joints with ring-stiffeners. Empirical models that can estimate SCF in composite reinforced joints for all combinations of joints and loads at multiple positions are required.

The empirical modelling of SCF is usually carried out using regression analysis of simulation results. Some analysed variance (ANOVA) using SPSS software [34,40,41,48], while others did not include any information about the technique and tool used. The efficiency of the developed empirical model strongly depends on the capability of the tool used for regression analysis. The investigation of various tools for regression analysis of different output parameters related to composite reinforced joints remains unexplored.

Very few studies have focused on the bond between joint and composite reinforcement, with a perfect bond assumption found reasonable [17], while another study found that increased adhesive layer thickness undermined the reinforcement effect [32]. Further research can consider the effect of ageing and the physical aspects of the bond.

Most of the articles reviewed have focused on uniplanar joints. The effect of multilinearity on composite-reinforced CHS joints needs to be investigated. Similarly, few studies focused on the probability distribution of SCF in the composite reinforced joints. Similar investigations for all other joints, load cases, and reinforcements can be conducted in the future. Most existing studies have concentrated on T/Y, K, X, and KT-joints, while more complex joints such as multiplanar XT, XK, KT, TKT, KKTT, and others require further exploration, particularly for the development of empirical equations. These joints are commonly employed in the construction of offshore platforms.

5. Conclusion

This review encompasses all research on the composite reinforcement of circular hollow section tubular joints. A systematic literature review was carried out according to PRISMA-2020 guidelines. The literature was searched through Google Scholar, Web of Science, and Scopus, resulting in twenty-four articles for critical review and evaluation. It was found that certain aspects were repeatedly investigated while others were overlooked. Future research needs to target these unexplored areas. The identified future avenues are the reinforcement of joints subjected to combined loads, identification of optimal layup orientation, S-N curves for FRP reinforced joints, and empirical equations for stress concertation factors along the weld toe. While most studies have focused on planar T/Y, K, X, TT, and KT-joints, there is a need to explore multiplanar complex joints, especially for the development of empirical equations. Exploring the utilisation of new regression analysis tools for developing efficient mathematical models is also an attractive field for future study. Moreover, the physical aspects of the composite application to tubular joints, fabrication processes, and ageing of composite reinforced joints also need to be explored. In summary, this article provides an overview of the state of the art of composite reinforcement of tubular joints and identifies various avenues for future research.

CRediT authorship contribution statement

Mohsin Iqbal: Writing – original draft, Formal analysis, Conceptualization. **Saravanan Karuppanan:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Veeradasan Perumal:** Supervision. **Mark Ovinis:** Writing – review & editing, Supervision. **Muhammad Iqbal:** Methodology, Conceptualization.

Declaration of competing interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Data availability

No data was used for the research described in the article.

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