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博士学位论文

粘贴碳纤维复合材料改善焊接接头和 含缺陷钢板的疲劳性能研究

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carbon fibre reinforced polymer materials**

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摘要

钢结构构件在服役过程中，受到外界荷载和环境因素的共同作用，疲劳裂纹易从应力集中处萌生、扩展。近年来，粘贴纤维复合材料补强成为一种新兴的钢结构疲劳损伤修补方式。已有研究表明，粘贴碳纤维复合材料（Carbon fibre reinforced polymer-CFRP）补强，能够有效改善钢构件疲劳性能。但是现有的研究大多关注于 CFRP 补强含微小人工缺陷的试件，有必要对 CFRP 补强含先天细小缺陷的焊接结构和不同程度初始损伤的构件展开进一步研究。

选取非承重十字型焊接接头，研究其粘贴 CFRP 布补强后的疲劳性能，主要考虑 CFRP 补强率的影响。试验过程中观察到试件在焊趾处或母材处断裂。补强后试件疲劳强度提高 16.2%-29.1%。

继而采用有限元数值方法，对此类焊接接头焊趾处应力集中系数和裂纹尖端应力强度因子进行参数分析。主要考虑了焊趾半径、补强率、补强材料弹性模量、裂纹深度和单/双面粘贴等多种因素的影响。计算结果表明，相比未补强试件，应力集中系数和应力强度因子在补强试件中下降趋势明显。焊趾半径和补强率是影响此类焊接接头疲劳性能的重要因素。提高 CFRP 布和粘结材料的弹性模量有助于进一步提高补强效果。

对 21 个平面外纵向焊接接头试件进行疲劳试验，分别采用 CFRP 布和 CFRP 板双面粘贴补强。试验过程中记录试件破坏模式和对应的疲劳寿命。发现疲劳裂纹从焊趾处萌生，逐步扩展直至试件断裂破坏。试验数据略显离散，补强试件疲劳寿命最多延长至 135%。

类似地，采用有限元方法对试验试件进行建模，分析补强后试件焊趾处应力集中系数的变化情况。参数分析结果表明，粘贴 CFRP 材料补强能够有效改善此类焊接接头焊趾处应力集中程度，降低钢板应力场。补强率的增加有利于提高试件疲劳性能。采用较高弹性模量的 CFRP 材料可以获得更好的补强效果，且这种趋势在 CFRP 板补强体系中更为明显。已有的数据显示，粘结材料弹性模量对应力集中系数影响不大。进一步采用边界元方法分析经 CFRP 补强的此类焊接接头疲劳裂纹扩展全过程。首先通过对比数值结果和文献中 CFRP 板补强含单面焊接钢板的试件试验结果来验证该方法，继而对补强体系中单/双面补强、单/双面焊接和 CFRP 弹性模量等因素进行研究分析。计算结果表明，双面粘贴 CFRP 板补强更为有效。双面焊接试件相比单面焊接试件疲劳寿命较短。对于双面粘贴试件，提高 CFRP 板弹性模量能够有效提高补强效率；而对于单面粘贴试件，CFRP 弹性模量对试件疲劳寿命影响不大。

为了剔除焊缝内初始缺陷和焊趾几何参数离散性对研究结果的影响,进一步调查初始疲劳损伤对 CFRP 补强钢构件疲劳性能的影响,采用含不同长度线裂纹的钢板试件进行疲劳试验,以研究在不同程度疲劳损伤情况下粘贴 CFRP 材料的补强效率。同时考虑了补强粘贴方式和 CFRP 弹性模量的影响。试验结果表明,不论初始损伤程度如何,采用 CFRP 材料补强均能够有效减缓裂纹扩展速率,延长试件残余疲劳寿命。采用高弹性模量 CFRP 板、覆盖初始裂纹粘贴和在裂纹扩展初期(损伤程度较小)采取补强措施,能够进一步提高补强效率。

采用有限元方法对含缺陷钢板裂纹尖端应力强度因子进行参数分析。变量包括裂纹长度、单/双面粘贴和 CFRP 板弹性模量。数值结果表明,在裂纹扩展后期采取补强措施,应力强度因子下降更为明显。单面补强钢板试件,存在平面外弯曲的现象,相比双面粘贴试件补强效率降低。提高 CFRP 板弹性模量,对双面或单面补强钢板试件,均能够大幅降低裂纹尖端的应力强度因子值。同时采用边界元方法对此类试件疲劳裂纹扩展全过程进行分析。预测得到的疲劳裂纹扩展过程及疲劳寿命和试验结果吻合良好,表明边界元法能够有效预测 CFRP 板补强钢板的疲劳性能。在此基础上,采用边界元模型对补强体系中的重要参数,包括粘贴长度、补强率、CFRP 板弹性模量以及粘结层剪切模量进行分析,研究它们对裂纹尖端应力强度因子的影响。参数分析结果显示,补强体系中存在一个有效粘结长度。相比普通弹性模量 CFRP 补强体系,高弹性模量 CFRP 补强体系中的有效粘结长度较大。随着补强率的增加,裂纹尖端应力强度因子明显下降。采用高弹性模 CFRP 材料能够达到更好的补强效果。提高粘结层剪切模量能够降低补强钢板裂纹尖端应力强度因子,但当粘结层剪切模量超过 350 MPa 后,应力强度因子下降速率明显减缓。

采用线弹性断裂力学,基于未补强钢板裂纹尖端应力强度因子经典解法,考虑补强后钢板中应力场的变化和由此引起的几何修正系数变化,提出 CFRP 补强含中心缺陷钢板裂纹尖端应力强度因子计算方法。采用论文和文献中试验结果比较验证,试验数据涵盖多种不同参数,包括不同程度初始缺陷、补强材料几何尺寸及力学性能和补强粘贴方式等。结果表明,这种方法能够偏于保守地计算粘贴 CFRP 的含缺陷钢板裂纹尖端应力强度因子,且结果合理准确。进一步采用这种方法分析 CFRP 弹性模量、补强率和粘贴长度对裂纹尖端应力强度因子的影响。数值计算结果的趋势和边界元方法参数分析结论一致。

论文拓展了 CFRP 补强焊接接头和含不同程度初始损伤构件方面的研究,并对这种补强方法提出了一些建议。为不同形式焊接接头的疲劳曲线提供基础数据,为设计修缮提供理论依据。

关键词：CFRP，焊接接头，含缺陷钢板，疲劳裂纹，初始损伤程度，应力强度因子

ABSTRACT

Fatigue cracks may initiate and grow in areas of stress concentration in steel structures. Recently, composite fibre patching techniques have been considered as alternatives to traditional methods of fatigue crack repair in steel structures. Research on using of carbon fibre reinforced polymer (CFRP) materials in steel structures has demonstrated their potential in enhancing fatigue behaviour of metallic structures. However, most previous research focused on a CFRP bonded specimen with an artificial and small notch. Further study is necessary to investigate the effectiveness of this strengthening method when applied to welded joints where initial defects exist and to steel elements with different degrees of damage.

A series of experiments were conducted to study the fatigue performance of CFRP-sheet repaired non-load-carrying cruciform welded joints. Different strengthening ratios were considered. It was observed that the specimens fractured at the weld toes or base plates. The fatigue strength of CFRP bonded specimens was increased from 16.2% to 29.1% in comparison with that of plain specimens.

Afterwards, numerical analysis was carried out to study stress concentration factor (SCF) values at weld toes and stress intensity factor (SIF) values at crack tips of these specimens. Variables including the weld toe radius, strengthening ratio, Young's modulus of retrofitting materials, crack depth and patching side were evaluated. It was found that both the SCF and the SIF could be significantly reduced after CFRP repairing. The weld toe radius and strengthening ratio were the key parameters influencing the fatigue behaviour of these welded joints. Enhancement of the elastic modulus of CFRP sheets and adhesive could be beneficial to the fatigue performance.

21 out-of-plane gusset welded joints strengthened with CFRP sheets or laminates were also tested under fatigue loading. Their fatigue lives and failure modes were recorded during the experiments. All cracks initiated from weld toes on the base plates that were adjacent to the longitudinal plate ends, and propagated gradually till specimen failure. The fatigue life of the welded joints with CFRP strengthening could be increased up to 135% over un-strengthened specimens, although scatters were observed from the test results.

Similarly, SCF values at weld toes were studied based on the finite element method. Parametric analysis showed that the SCF values were considerably brought

down after strengthening. A higher strengthening ratio would result in a better fatigue behaviour. It was available to improve the strengthening efficiency by using high modulus CFRP materials and this trend was more pronounced in the CFRP-laminate repair system. No obvious influence was found regarding the stiffness of the adhesive layer based on the limited results. The study of the fatigue behaviour of CFRP repaired out-of-plane welded joints was expanded using the boundary element method. This method was first validated by the good agreement between numerical data and experimental results of steel plates with longitudinal weld attachments strengthened by CFRP laminates on one side from the literature. Thereafter, the effects of single/double side strengthening, single/double side weld attachment and CFRP stiffness on the fatigue behavior of retrofitted welded joints were further discussed. It was indicated that the double-sided repair was more efficient. In comparison with steel plates with attachments on only one side, the fatigue life of double-sided welded specimens appeared shorter. The elastic modulus of CFRP laminates had a considerable influence on the specimens with composite materials attached on both sides. While for the single-sided strengthened specimens, the improvement of the fatigue behaviour by using ultra-high modulus CFRP laminates was limited.

To exclude the scatter effect of welding and further examine the matter of initial defects, an experimental study on artificial cracked steel plates was carried out to evaluate the influence of various degrees of initial damage on the fatigue performance of CFRP-strengthened elements. Parameters of the retrofitting configuration and CFRP stiffness were also studied. The experimental results were very encouraging, demonstrating that CFRP patches could effectively slow crack growth and extend fatigue lives, regardless of the initial damage levels. More remarkable strengthening effect was found by using ultra-high modulus CFRP laminates, covering the initial cracks with CFRP and repairing at an earlier stage (i.e., smaller damage level).

The SIF values at crack tips of cracked steel plates strengthened with CFRP laminates were calculated by using the finite element method. Effects considered included the crack length, patch side and elastic modulus of CFRP laminates. Numerical results showed that the CFRP-laminate bonding repair could significantly reduce SIF values at crack tips. Regardless of the crack lengths, the strengthening method was effective at all stages of crack propagation and later application brought about more considerable effect. Without out-of-plane bending, double-side repair was better if applicable. The use of CFRP laminates with high modulus could also improve

the strengthening effectiveness. Crack propagation analysis on these cracked steel plates (with different degrees of damage) repaired by CFRP laminates was also performed using the boundary element method. The predicted crack propagation and fatigue lives were compared well with the experimental data, which demonstrated that the boundary element method was reliable for crack propagation analysis of CFRP-laminate retrofitted steel plates. Finally, a parametric analysis was conducted to investigate the influence of the bond length, strengthening ratio, CFRP stiffness and adhesive shear modulus on SIF values. It was demonstrated that an optimum bond length existed in the strengthening system. The optimal bond length in an ultra-high modulus CFRP bonded specimen was observed to be longer than that in a normal modulus CFRP repaired specimen from the numerical analysis. The SIF values decreased continuously as the strengthening ratio increased. Repair materials with higher elastic modulus could lead to more pronounced strengthening effect. However, when the adhesive shear modulus was further increased over 350 MPa, the reduction ratio comparatively slowed down.

Based on the classical solution of SIF values at crack tips of plain steel plates, a new approach was proposed to evaluate the SIF values at crack tips of steel plates strengthened with bonded composite materials by using linear elastic fracture mechanics. The load share effect and geometry correction factor change resulted from the overlay patch were evaluated. Effects of different parameters were demonstrated and compared with experimental results, including initial damage degrees of the specimens, geometric and mechanical properties of the retrofitting materials and bond locations. Good agreement with the experimental data indicated that this approach could conservatively predict the SIF values with reasonable accuracy. A parametric study on variables including the CFRP modulus, strengthening ratio and bond length was conducted based on this method to investigate their influence on the SIF values. The general trend showed good consistency with the results obtained by using the boundary element analysis.

This research extends the understanding of CFRP application to welded joints and steel elements with different degrees of damage. Some useful suggestions for this strengthening method are proposed. The test database contributes to the development of this retrofitting method in fatigue crack repair of steel structures.

Key Words: CFRP, welded joint, cracked steel plate, fatigue crack, degree of damage, stress intensity factor

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第 1 章 引言

1.1 研究背景

建筑业研究与信息协会 (Construction Industry Research and Information Association-CIRIA) [1] 报告指出, 世界范围内存有大量建于 19 世纪末 20 世纪初的金属结构基础设施, 包括工业建筑、桥梁、高架桥和地铁等。美国有 12 万座以上含有焊接接头的钢桥, 其中超过 5 万座已经服役 30 年以上。据统计研究, 大多公路桥梁每年需承受 150 万次通行车辆荷载, 折合在 100 年服役寿命中约要承受 10,000 万次应力循环, 有些甚至高达 30,000 万次 [2]。因此, 美国国有公路运输管理员协会 (American Association of State Highway and Transportation Officials-AASHTO) 中规定的 200 万次疲劳寿命设计要求其实远低估了工程实际需求。这些建筑结构中的钢构件在使用过程中受到外荷载和环境因素的共同作用, 产生各种损伤, 如焊接钢桥的疲劳裂纹和环境腐蚀, 直接影响结构的使用功能, 甚至造成灾难性的事故, 如 1994 年韩国 Seongsu 大桥倒塌事故 [3] 和 2000 年美国威斯康星州 Hoan 大桥断裂事故 [4]。事故调查结果表明, 疲劳损伤累积是裂纹出现和扩展的主要原因, 进而造成大桥的突然断裂。我国近年来兴建的大量钢结构桥梁和钢-混凝土组合桥梁在使用寿命期内亦要承受大量车辆循环荷载, 其疲劳性能将是设计和使用过程中的重要关注对象。同时, 随着经济发展, 汽车通行数量不断增加, 基础结构设施实际承受荷载超过设计安全范围的风险也在不断增加。因此, 研究如何修复损伤后的钢结构, 提高承载能力, 维护正常使用性能, 延长疲劳寿命, 是土木工程领域的一项重要内容。

工程师们采用各种方法对疲劳损伤的钢结构进行补强。新近出现的粘贴碳纤维复合材料法 [5], 所采用的 CFRP 材料是继钢材和混凝土之后的第三大现代结构材料, 具有强度高、耐腐蚀、自重轻、体积小、补强效果好和施工方便等特点 [6][7], 在国内外工程界应用愈加广泛。粘贴复合材料补强方法最早于始于 20 世纪 70 年代航空工业领域 [8], 随着研究的不断深入和拓宽, 其应用范围逐渐从航空业 [7][9][10][11][12][13][14][15][16][17] 拓展到土木工程领域 [18][19][20]。70 年代末 80 年代初, 碳纤维复合材料开始应用于桥梁结构中。迄今为止, 世界范围内最大规模采用 CFRP 材料补强修复的工程结构为澳大利亚墨尔本市 West Gate 大桥 [21]。

在土木工程领域, 粘贴 CFRP 材料补强已在混凝土结构和砌体结构中得到广泛的研究和应用 [22][18], 但在钢结构中的研究尚处在起步阶段 [23][24][25], 特别是对于疲劳裂纹易于出现的焊接接头更是少有。大量的钢结构建筑, 例如桥梁和海上