Experimental investigation on ultimate strength and failure response of composite box beams used in wind turbine blades

This study focuses on the ultimate strength and failure response of composite box beams under three-point bending. The box beams consist of spar caps and shear webs and they are typically used in wind turbine blades as load-carrying members. Different spar cap configurations and loading directions are examined experimentally to investigate structural behavior associated with multiple nonlinearities leading to structural collapse. Global displacements, local strains and video images are recorded throughout the loading history to capture failure initiation, propagation and the strain state contributing to post-collapse characteristics. The failure mechanisms of the box beams involving geometric, material and contact nonlinearities are discussed in detail. The study shows that compressive crushing failure, driven by local buckling of shear webs, determines the ultimate strength of the box beams under flapwise loading, and adhesive joint debonding, initiated by local adhesive cracking and spar cap buckling, is the critical failure mode of the box beams under edgewise loading. The Brazier effect and shear nonlinearity contribute to the initial failure depending on the loading directions. Debonding rather than delamination characterizes post-collapse behavior of all box beams examined in this study.
Fracture of wind turbine blades in operation-Part I: A comprehensive forensic investigation

The structural integrity of rotor blades is crucial to ensuring continuous power production of wind turbines. Catastrophic blade fracture can cause significant economic loss and social impact and thereby should be prevented. It is important to understand the structural failure of rotor blades particularly during their normal operation. This study presents a comprehensive forensic investigation into fracture of 2 rotor blades in the field. The investigation is carried out synthetically taking into account interactive aspects associated with operational loads, materials, manufacturing processes, and structural design. The supervisory control and data acquisition data are analyzed to understand the turbine response with damaged blades. A detailed post-mortem investigation is carried out at structural, subcomponent, and material levels both
in field and in laboratory from a forensic perspective. Different manufacturing-induced defects are examined using X-ray computed tomography, and they are discussed in the context of the current manufacturing and design practices. Evidences from macroscopic failure features and microscopic fractographic morphologies are collected, analyzed, and correlated in order to identify the underlying mechanisms of blade fracture. Practices are recommended to improve structural integrity of rotor blades during their entire life cycles.

**General information**
State: Published
Organisations: Department of Wind Energy, Wind Turbine Structures and Component Design
Contributors: Chen, X.
Number of pages: 18
Pages: 1046-1063
Publication date: 2018
Peer-reviewed: Yes

**Publication information**
Journal: Wind Energy
Volume: 21
Issue number: 11
ISSN (Print): 1095-4244
Ratings:
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 3.18 SJR 1.051 SNIP 1.834
Web of Science (2017): Impact factor 2.938
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.37 SJR 1.079 SNIP 2.316
Web of Science (2016): Impact factor 2.725
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 3.06 SJR 1.201 SNIP 2.165
Web of Science (2015): Impact factor 2.891
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 3.42 SJR 1.209 SNIP 3.688
Web of Science (2014): Impact factor 3.069
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 2.75 SJR 1.235 SNIP 2.486
Web of Science (2013): Impact factor 2.556
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 2.36 SJR 1.062 SNIP 2.297
Web of Science (2012): Impact factor 1.436
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 2.49 SJR 0.892 SNIP 2.582
Web of Science (2011): Impact factor 1.768
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 1.364 SNIP 2.026
Web of Science (2010): Impact factor 1.716
Experimental investigation on structural collapse of a large composite wind turbine blade under combined bending and torsion

This study presents a comprehensive investigation on structural collapse of a 47 m composite blade under combined bending and torsion in a full-scale static load test. The primary focus is placed on root causes and failure mechanism of the blade collapse. The investigation consists of three parts. First, video records of the blade collapse are examined on a frame-by-frame basis. Direct evidence is presented on how the blade collapses in progressive chain events. Second, the detailed post-collapse investigation is conducted both in-situ and in laboratory. The critical failure modes and the associated stress/strain state once experienced by the blade are indentified. Third, strain measurements are analyzed to provide quantitative evidence of the process leading to the blade collapse and consequently confirm the findings of this study. It is found that longitudinal compressive crushing failure and the following delamination of the spar cap, which are driven by local buckling, are the root causes of the blade collapse. The constraint of the loading saddle and local reinforcement of the blade section also contributes to the blade collapse. Torsion loads, although exhibiting no significant effect on the blade strength, are found to affect post-collapse characteristics of the blade.

**General information**
State: Published
Organisations: Chinese Academy of Sciences
Contributors: Chen, X.
Number of pages: 11
Pages: 435-445
Publication date: 15 Jan 2017
Peer-reviewed: Yes

**Publication information**
Journal: Composite Structures
Volume: 160
ISSN (Print): 0263-8223
Ratings:
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Collapse of a 47-meter composite blade under combined bending and torsion in a full-scale static test

This study presents an investigation on structural collapse of a large composite wind turbine blade under combined bending and torsion in a static load test. The initial failure phenomenon prior to the blade collapse is investigated using video recorded images. Postcollapse characteristics of the blade are examined to identify the critical failure modes. A finite element model is constructed considering the constraint effect of loading saddles on the blade section. Structural response of the blade section during the loading process is investigated numerically. It is found that delamination and fracture of the spar cap are two critical failure modes responsible for the root causes of the blade collapse. These critical failure modes are evoked by local buckling of blade shells and shear webs. Numerical results show that the Brazier effect imposes significant crushing pressure to the blade cross section and contribute to local buckling. Moreover, it is found that torsion loads, although insignificant compared with the primary bending loads applied to the blade, affect postcollapse characteristics of the blade in this study.

Revisiting the structural collapse of a 52.3 m composite wind turbine blade in a full-scale bending test: Structural collapse of a 52.3 m composite wind turbine blade

Full-scale structural tests enable an in-depth understanding of how composite blades respond to specific applied loads. Blade strength can be validated, and necessary modifications can be made to improve structural performance and/or reduce blade weight. This study revisits the structural collapse of a 52.3m composite blade with new research content. Specifically, the present work examines the chain of events captured in the video record of the blade collapse and provides direct phenomenological evidence of how the blade collapsed in its ultimate limit state. In addition, three-dimensional strains are investigated by reconstructing the root transition region of the blade using solid brick elements in a finite element analysis. The strain components responsible for particular failure characteristics are identified. The structural response of the blade is investigated numerically. Interactive failure phenomena associated with strains, local buckling and material failure are examined in detail. The study shows that local buckling of the sandwich panels with unbalanced construction drives progressive failure of the composite materials and eventually leads to blade collapse owing to significant failure of the load-carrying spar cap. Design modifications of the blade are proposed and validated with the test of a new blade. With respect to the latest DNV GL standard, this study notes a possible method to predict delamination and skin/core debonding failures. This study also recommends the use of three-dimensional solid elements in finite element analysis, especially when the strength and failure of large blades are of concern. Copyright (c) 2017 John Wiley & Sons, Ltd.
Ratings:
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 3.18 SJR 1.051 SNIP 1.834
Web of Science (2017): Impact factor 2.938
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.37 SJR 1.079 SNIP 2.316
Web of Science (2016): Impact factor 2.725
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 3.06 SJR 1.201 SNIP 2.165
Web of Science (2015): Impact factor 2.891
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 3.42 SJR 1.209 SNIP 3.688
Web of Science (2014): Impact factor 3.069
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 2.75 SJR 1.235 SNIP 2.486
Web of Science (2013): Impact factor 2.556
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 2.36 SJR 1.062 SNIP 2.297
Web of Science (2012): Impact factor 1.436
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 2.49 SJR 0.892 SNIP 2.582
Web of Science (2011): Impact factor 1.768
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 1.364 SNIP 2.026
Web of Science (2010): Impact factor 1.716
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 2
Scopus rating (2009): SJR 0.885 SNIP 1.439
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 0.743 SNIP 1.555
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 0.942 SNIP 1.42
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 0.586 SNIP 1.653
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 0.273 SNIP 0.827
Web of Science (2005): Indexed yes
Scopus rating (2004): SJR 0.525 SNIP 0.845
Web of Science (2004): Indexed yes
Web of Science (2003): Indexed yes
Structural degradation of a large composite wind turbine blade in a full-scale fatigue test

Wind turbine blades are expected to sustain a high number of loading cycles typically up to a magnitude of 1,000 million during their targeted service lifetime of 20-25 years. Structural properties of composite blades degrade with the time. Although substantial studies, such as [1,2], have been carried out at a coupon level to characterize fatigue degradation of composite materials, there is no much study focusing on fatigue degradation of rotor blades at a full scale structural level. Do structural properties of composite blades degrade in a similar manner to what has been observed in material tests at a coupon level? What might be the concerns one should take into account when predicting residual structural properties of rotor blades? To answer, at least to a partial extent, these questions, this study conducts a full-scale fatigue test on a 47m composite rotor blade according to IEC 61400-23 (ed. 2014). A conventional single-axis mass resonance excitation (rotating mass) method is used as it is now still widely used for blade certification. The blade is tested in a flap-wise bending direction with the suction side primarily under compressive stress and pressure side under tensile stress, see Fig. 1. The applied loads are increased to reduce the number of cycles to 2.0 million cycles. Bending stiffness of the blade is measured at different span-wise sections during the fatigue test in order to measure its possible degradation. Natural frequencies and damping ratios are measured both before and after fatigue test. Post-fatigue damage of the blade is examined throughout the blade. It is found that the blade exhibited different stiffness degradation patterns at different cross sections. As shown in Fig. 2, the bending stiffness of the blade from 0 to 19 m did not show obvious degradation during fatigue test. However, the bending stiffness of the blade from 0 to 28 m and that from 0 to 39.5 m showed very similar degradation pattern to composite materials, which is fast at the early stage and slow at the following stage. In addition, it is noted that the overall stiffness degradation is shown to be not significant.

General information
State: Published
Organisations: Department of Wind Energy, Wind Turbine Structures and Component Design
Contributors: Chen, X.
Number of pages: 4
Publication date: 2017
Peer-reviewed: Yes

Electronic versions:
Structural_degradation_of_a_large_composite_wind_turbine_blade_in_a_full_scale_fatigue_test.pdf
Source: PublicationPreSubmission
Source-ID: 139722558
Research output: Research - peer-review › Conference abstract for conference – Annual report year: 2017

Structural integrity of wind turbines impacted by tropical cyclones: A case study from China

This study presents a case study on wind turbines impacted by tropical cyclones in China. A quantitative investigation is conducted by integrating aerodynamic, aero-elastic and structural analysis to provide insights into structural integrity of wind turbines under extreme wind conditions. Local mean wind profiles at each turbine site are reconstructed using three-dimensional CFD calculation considering terrain topography of the wind farm. Failure modes and failure locations of rotor blades and tubular towers are predicted using finite element analysis. "The lesser of two evils" principle in the turbine design is addressed regarding the criticality of blade fracture and tower collapse. Referring to the current IEC standard for wind turbine design, it is suggested that the partial safety factor associated with failure of turbine tower should be larger than, instead of equal to, the one for the rotor blade to reduce the risk of the total loss of wind turbines in extreme wind conditions.

General information
State: Published
Organisations: Chinese Academy of Sciences
Contributors: Chen, X., Li, C., Tang, J.
Publication date: 3 Oct 2016
Peer-reviewed: Yes
Structural failure analysis of wind turbines impacted by super typhoon Usagi

Extreme winds severely endanger structural integrity of wind turbines. In order to understand failure mechanisms of wind turbine structures under extreme wind conditions, this paper presented a study on structural failure of wind turbines damaged by super typhoon Usagi in 2013. A particular focus was placed on the effect of strong wind speed and large change of wind direction on tower collapse and blade fracture. Post-mortem investigation was conducted at field, and data of local winds, tubular steel tower and composite rotor blade were collected and analyzed. A systematic procedure was developed by integrating wind load calculation and structural modeling. Quantitative investigation on structural response of turbine towers and rotor blades was conducted to identify the root causes of failure. Failure scenarios were studied considering typical stop positions of the wind turbine. The fuse function of the rotor blade whose fracture is able to protect the tower from collapse was also addressed. Based on the findings obtained from this study, some suggestions were proposed to modify the current IEC design standard and a few potential future directions of study were addressed to reduce the risk of wind turbine failure under extreme wind conditions such as typhoon and hurricane.
Failure investigation on a coastal wind farm damaged by super typhoon: A forensic engineering study

This study presented a failure investigation on a wind farm which is located on the southeast coast of Mainland China and was severely damaged by two super typhoons: i.e., Dujuan in 2003 and Usagi in 2013. Failure characteristics of the wind farm in terms of rotor blade damage, tubular tower collapse and wind turbine (WT) burn were examined from a forensic engineering perspective. A systematic procedure was proposed to quantitatively investigate structural failure by calculating the extreme wind loads and re-constructing structural models for composite blades and steel towers. It was found that both extreme winds and the stop positions of WTs were critical to turbine failure due to the change of wind direction during typhoon impact. The overstrain/overstress was identified as the plausible root cause for structural failure of WTs. In addition, the dramatic reduction of shell wall thickness due to possible design defect was also found to be responsible for the tower collapse in this study. (C) 2015 Elsevier Ltd. All rights reserved.

General information
State: Published
Organisations: Chinese Academy of Sciences
Contributors: Chen, X., Li, C., Xu, J.
Pages: 132-142
Publication date: 2015
Peer-reviewed: Yes

Publication information
Journal: Journal of Wind Engineering and Industrial Aerodynamics
Volume: 147
ISSN (Print): 0167-6105
Ratings:
BFI (2018): BFI-level 1
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 3.42 SJR 1.264 SNIP 2.071
Web of Science (2017): Impact factor 2.689
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 2.61 SJR 0.992 SNIP 1.929
Web of Science (2016): Impact factor 2.049
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 2.51 SJR 0.976 SNIP 1.939
Web of Science (2015): Impact factor 2.024
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 2.13 SJR 0.902 SNIP 2.282
Web of Science (2014): Impact factor 1.414
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 2.43 SJR 0.8 SNIP 2.68
Web of Science (2013): Impact factor 1.698
Post-mortem study on structural failure of a wind farm impacted by super typhoon Usagi

Super typhoon Usagi, which was on category 4 according to the Saffir-Simpson hurricane intensity scale [1], impacted a wind farm near Shanwei city on the southeast coast of China in 2013, see Figure 1. During typhoon impact, the wind farm experienced a dramatic change of wind direction and a maximum wind speed (3s average) of 57 m/s at a 10-m elevation. As a result of this super typhoon, eight turbine towers collapsed, eleven rotor blades broke off and three turbines were burned, leading to an approximate $16 million loss to the wind farm. Authors of this paper carried out a post-mortem study on the wind farm with particular focus on the tower collapse and blade failure. A systematic procedure was developed for this endeavor by integrating both aerodynamic analysis for wind characterization and structural analysis for towers and blades. To provide necessary input for the procedure, data of local wind record, terrain topography and turbine status were collected, analyzed and assessed together with field investigation and user inquiry. Through this study, plausible root-causes of structural failure of the wind farm were indentified. This paper summarized the process and key findings of structural failure investigation on the wind farm impacted by super typhoon Usagi. It is expected that insights gained from this study could assist structural failure mitigation of wind farms under extreme wind conditions.

General information
State: Published
Failure test and finite element simulation of a large wind turbine composite blade under static loading

This study presented a failure analysis of a 52.3 m composite wind turbine blade under static loading. Complex failure characteristics exhibited at the transition region of the blade were thoroughly examined and typical failure modes were indentified. In order to predict multiple failure modes observed in the tests and gain more insights into the failure mechanisms of the blade, a Finite Element (FE) simulation was performed using a global-local modeling approach and Progressive Failure Analysis (PFA) techniques which took into account material failure and property degradation. Failure process and failure characteristics of the transition region were satisfactorily reproduced in the simulation, and it was found that accumulated delamination in spar cap and shear web failure at the transition region were the main reasons for the blade to collapse. Local buckling played an important role in the failure process by increasing local out-of-plane deformation, while the Brazier effect was found not to be responsible for the blade failure.
Numerical analysis and experimental investigation of wind turbine blades with innovative features: Structural response and characteristics

Innovative features of wind turbine blades with flatback at inboard region, thick airfoils at inboard as well as mid-span region and transversely stepped thickness in spar caps have been proposed by Institute of Engineering Thermophysics, Chinese Academy of Sciences (IET-Wind) in order to improve both aerodynamic and structural efficiency of rotor blades. To verify the proposed design concepts, this study first presented numerical analysis using finite element method to clarify the effect of flatback on local buckling strength of the inboard region. Blade models with various loading cases, inboard configurations, and core materials were comparatively studied. Furthermore, a prototype blade incorporated with innovative features was manufactured and tested under static bending loads to investigate its structural response and characteristics. It was found that rotor blades with flatback exhibited favorable local buckling strength at the inboard region compared with those with conventional sharp trailing edge when low-density PVC foam was used. The prototype blade showed linear behavior under extreme loads in spar caps, aft panels, shear web and flatback near the maximum chord which is usually susceptible to buckling in the blades according to traditional designs. The inboard region of the blade showed exceptional load-carrying capacity as it survived 420% extreme loads in the experiment. Through this study, potential structural advantages by applying proposed structural features to large composite blades of multi-megawatt wind turbines were addressed.

General information
State: Published
Organisations: Chinese Academy of Sciences
Contributors: Chen, X., Qin, Z. W., Yang, K., Zhao, X. L., Xu, J. Z.
Number of pages: 8
Publication date: 2014
Peer-reviewed: Yes

Publication information
Journal: Science China Technological Sciences
Volume: 58
Issue number: 1
ISSN (Print): 1674-7321
Ratings:
Web of Science (2018): Indexed yes
Scopus rating (2017): CiteScore 1.95 SJR 0.537 SNIP 0.908
Web of Science (2017): Impact factor 1.938
Web of Science (2017): Indexed yes
Scopus rating (2016): CiteScore 1.69 SJR 0.499 SNIP 1.047
Web of Science (2016): Impact factor 1.719
Scopus rating (2015): CiteScore 1.54 SJR 0.566 SNIP 1.052
Web of Science (2015): Impact factor 1.441
Scopus rating (2014): CiteScore 1.45 SJR 0.573 SNIP 1.361
Preliminary failure investigation of a 52.3 m glass/epoxy composite wind turbine blade

Despite the enthusiastic pursuing for large wind turbine blades to reduce the cost of wind power, wind energy industry has witnessed a number of catastrophic blade failure accidents in recent years. In order to provide more insights into the failure of large blades, this short communication presents preliminary investigation on a 52.3 m composite blade designed for multi-megawatt wind turbines. Static loads were applied to simulate extreme load conditions subjected by the blade. After blade failure, visual inspection was carried out and failure characteristics of the blade were examined. It was found that the blade exhibited multiple failure modes. Among various failure modes observed, delamination of unidirectional laminates in the spar cap was identified to be the plausible root cause of the catastrophic failure of the blade. This study emphasized that through-thickness stresses can significantly affect the failure of large composite blades and provided some suggestions to the current design practices. (C) 2014 Elsevier Ltd. All rights reserved.

General information
State: Published
Organisations: Chinese Academy of Sciences
Contributors: Chen, X., Zhao, W., Zhao, X. L., Xu, J. Z.
Pages: 345-350
Publication date: 2014
Peer-reviewed: Yes

Publication information
Journal: Engineering Failure Analysis
Volume: 44
ISSN (Print): 1350-6307
Ratings:
BFI (2018): BFI-level 1
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 2.41 SJR 0.933 SNIP 1.777
Web of Science (2017): Impact factor 2.157
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
A 10.3 m wind turbine (WT) blade has been designed to improve structural efficiency of rotor blades. The blade was featured with glass/polyester composites, flatback in the inboard region, thick airfoils in the mid-span region and transversely stepped spar cap thickness. This paper provided an overview of static bending test performed on the blade. Deflections, strains, load-carrying capacity, and failure behavior of the blade were investigated. Finite element (FE) analysis was carried out to complement test and to provide more insights into structural performance of the blade. The blade exhibited linear behavior in spar caps and aft panels at the maximum chord, and it continued to withstand applied loads well beyond the occurrences of local buckling of the shear web and the flatback at the maximum chord. The inboard...
region showed exceptional load-carrying capacity with failure loads larger than 420% test loads. Through this study, potential structural advantages by applying proposed structural features to large composite blades for multi-megawatt (MW) wind turbines were addressed.

**General information**
State: Published
Organisations: Chinese Academy of Sciences
Contributors: Chen, X., Zhao, X. L., Qin, Z. W., Xu, J. Z.
Number of pages: 7
Publication date: 2014

**Host publication information**
Title of host publication: ASME 2014 International Mechanical Engineering Congress and Exposition
Volume: 9
Publisher: American Society of Mechanical Engineers
Article number: IMECE2014-39507
Keywords: Mechanical Engineering, Airfoils, Finite element method, Glass, Load limits, Loads (forces), Turbomachine blades, Wind turbines, Composite blades, Failure behaviors, Glass/polyester composites, Static bending tests, Structural advantage, Structural efficiencies, Structural feature, Structural performance, Turbine components
DOI: 10.1115/IMECE2014-39507
Source: FindIt
Source-ID: 2288731923
Research output: Research - peer-review › Article in proceedings – Annual report year: 2014

**Experimental Study on CFRP-bonded Steel Plates with Thickness Reduction using Underwater Epoxy**
This paper presents a series of uniaxial loading tests on the thickness-reduced steel plates bonded with carbon fiber reinforced polymer (CFRP) strand sheets using underwater epoxy as adhesive. Four sets of material test are carried out on epoxy coupons at different curing times. Repaired performance of CFRP-bonded steel plates is investigated in terms of initial stiffness, yield strength, and failure mode of the specimens. Test results showed that the structural performance of CFRP-bonded steel plates does not reach the expected design level due to a slow curing process of epoxy adhesive in this study. The curing effects of epoxy adhesive on the repaired performance are discussed.

**General information**
State: Published
Organisations: Nagoya University
Contributors: Chen, X., Kitane, Y., Itoh, Y.
Pages: 373-379
Publication date: 2012
Peer-reviewed: Yes

**Publication information**
Journal: Applied Mechanics and Materials
Volume: 117-119
ISSN (Print): 1660-9336
Ratings:
Scopus rating (2017): SJR 0.117 SNIP 0.178
Web of Science (2017): Indexed yes
Scopus rating (2016): SJR 0.116 SNIP 0.166
Scopus rating (2015): CiteScore 0.07 SJR 0.112 SNIP 0.074
Scopus rating (2014): CiteScore 0.09 SJR 0.149 SNIP 0.204
Scopus rating (2013): CiteScore 0.09 SJR 0.132 SNIP 0.2
ISI indexed (2013): ISI indexed no
Scopus rating (2012): CiteScore 0.1 SJR 0.123 SNIP 0.239
ISI indexed (2012): ISI indexed no
Scopus rating (2011): CiteScore 0.11 SJR 0.116 SNIP 0.258
ISI indexed (2011): ISI indexed no
Scopus rating (2010): SJR 0.139 SNIP 0.325
Scopus rating (2009): SJR 0.163 SNIP 0.332
Scopus rating (2008): SJR 0.227 SNIP 0.521
Scopus rating (2007): SJR 0.167 SNIP 0.207
Minimum thickness of welding patches to recover structural performance of steel pipe piles under compression

This paper presents an analytical study on a minimum patch thickness necessary to fully recover structural performance of corrosion-damaged pipe piles under axial compressive loads using welding repair. Load transfer mechanism, the repaired stiffness and strength of pipe piles are examined. An accurate calculation of load share ratio of patch plates considering weld stiffness is derived, and the results are compared with experimental results and finite element analysis results. The minimum thickness of patch plates to fully recover the stiffness and the design strength of the corrosion-damaged piles to their intact state considering the existing loads is proposed.

Tensile and Compressive Test on Thickness-Reduced Steel Plate Repaired by CFRP Strand Sheet and Underwater Epoxy with Bond Defects

There are a significant number of marine steel structures suffering severe corrosion damage, and they are seriously in need of repair or strengthening to prevent structural failure. This study is focused on a repair technique using carbon fiber reinforced polymer (CFRP) sheet, especially, CFRP sheet bonding in the underwater environment. Underwater bonding of CFRP sheets is not yet a matured technique, and its repair performance for corroded steel structures is not fully understood. One of the issues is the effect of bond defects on the repair performance. Air bubbles are often found to be trapped in the adhesive layer. To examine an effect of bond defects on the repair performance, uniaxial loading tests are performed on thickness-reduced steel plates with CFRP strand sheets bonded by using underwater epoxy as adhesive. In
total, sixteen CFRP strand sheet bonded steel plates are prepared, where test parameters are loading directions of
tension and compression and the location of bond defects. The effect of bond defects on the repaired performance is
examined in terms of yield strength, initial stiffness, and failure mode. As a result of experiment, it is found that two types
of defects considered in this study do not affect repair performance significantly. However, when a CFRP bonded steel
plate is under compression, buckling of CFRP strand sheet may control its compression strength, resulting in a smaller
strength than the tensile strength.

General information
State: Published
Organisations: Nagoya University, Kyoto University
Number of pages: 8
Publication date: 2012
Peer-reviewed: Yes
Electronic versions:
Tensile_and_Compressive_Test_on_Thickness_Reduced_Steel_Plate_Repaired_by_CFRP_Strand_Sheet_and_Underwat
er_Epoxy_with_Bond_Defects.pdf
Source: PublicationPreSubmission
Source-ID: 138914460
Research output: Research - peer-review » Paper – Annual report year: 2012

Compression behaviors of thickness-reduced steel pipes repaired with underwater welds
Underwater welding is commonly used to repair corroded offshore steel structures. Corrosion-damaged portions are
covered by welded patch plates. According to the current design manual, a thickness of patch plate and a weld length can
be determined. However, different weld patterns can be designed to achieve the same required weld length. In order to
examine the effectiveness of these different weld patterns, this paper first proposes a method to model underwater welds
in the finite element analysis based on mechanical properties of fillet welds obtained from weld strength tests. The weld
model was firstly validated against a theoretical shear stress distribution in a longitudinal fillet weld and then further
validated against experimental results of thickness-reduced steel pipes repaired with welded patch plates under
compression. The proposed model was then applied to thickness-reduced steel pipes repaired by welded patch plates
with different weld patterns that have the minimum required weld length. Behaviors of these repaired pipes under a
compressive load were examined with respect to stiffness, load-carrying capacity, load share of patch plates, and failure
modes. It was found that stiffness and load-carrying capacity of the thickness-reduced steel pipes under compression
cannot be fully recovered by the welded patch plate repair when a patch plate thickness is the same as the thickness
reduction of the damaged pipe. Among different weld patterns, the one with four slits was found to show better
performance.

General information
State: Published
Organisations: Nagoya University
Contributors: Chen, X., Kitane, Y., Itoh, Y.
Pages: 2699-2706
Publication date: 2011
Peer-reviewed: Yes

Publication information
Journal: Procedia Engineering
Volume: 14
ISSN (Print): 1877-7058
Ratings:
Scopus rating (2017): CiteScore 0.89
Web of Science (2017): Indexed yes
Scopus rating (2016): CiteScore 0.74
Scopus rating (2015): CiteScore 0.56
Scopus rating (2014): CiteScore 0.53
Scopus rating (2013): CiteScore 0.4
ISI indexed (2013): ISI indexed no
Scopus rating (2012): CiteScore 0.28
ISI indexed (2012): ISI indexed no
Scopus rating (2011): CiteScore 0.45
ISI indexed (2011): ISI indexed no
Evaluation of repair design on corrosion-damaged steel pipe piles using welded patch plates under compression

This paper presents a numerical study on the compressive behavior of steel pipe piles repaired with patch plates welded underwater. In this study, a uniform thickness reduction is assumed for a portion of a pipe pile to simulate corrosion damage, and a special attention is paid to modeling the mechanical behavior of fillet welds in finite element analysis based on available experimental data. Effectiveness of different welding patterns on pipe piles with various size parameters is examined in terms of stiffness, load-carrying capacity, and load share ratio of patch plates of repaired piles. Effectiveness of transverse welds in the repair is also examined, and equations to calculate a load share ratio of patch plates, the minimum thickness of patch plates, and the maximum number of slits are proposed for the repair design.

General information
State: Published
Organisations: Nagoya University
Contributors: Chen, X., Kitane, Y., Itoh, Y.
Publication date: 2011
Peer-reviewed: Yes

Publication information
Journal: Journal of Structural Engineering
Volume: 57A
ISSN (Print): 0733-9445
Ratings:
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 2.27 SJR 1.74 SNIP 1.733
Web of Science (2017): Impact factor 1.903
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 1.91 SJR 1.228 SNIP 1.834
Web of Science (2016): Impact factor 2.021
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 1.62 SJR 1.598 SNIP 1.918
Web of Science (2015): Impact factor 1.7
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 1.93 SJR 1.981 SNIP 2.477
Web of Science (2014): Impact factor 1.504
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 2.01 SJR 1.884 SNIP 2.608
Web of Science (2013): Impact factor 1.488
ISI indexed (2013): ISI indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 1.57 SJR 1.73 SNIP 2.112
Web of Science (2012): Impact factor 1.206
ISI indexed (2012): ISI indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 1.38 SJR 1.52 SNIP 2.028
Web of Science (2011): Impact factor 0.955
ISI indexed (2011): ISI indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 1.582 SNIP 1.757
Mechanical Properties of Fillet Weld Joints by Underwater Wet Welding in Repairing Corrosion-Damaged Offshore Steel Structures

This paper presents a series of experiments on fourteen different assemblies of fillet weld joints produced by both underwater and in-air welding. Mechanical properties of underwater fillet welds in terms of strength, ductility, and failure modes are investigated in this study. Weld profiles, hardness distributions, and metallographic features of underwater welds are also examined. The study indicates that underwater fillet weld joints have larger strength but smaller ductility when compared with their counterpart in-air ones. The increase in strength ranges from 6.9% to 41.0%, and the decrease in ductility is about 50% for most of weld assembly types. Underwater fillet weld joints on corroded SY295 steel exhibit inferior ductility due to underbead cracks. Based on the test results, the paper proposes a practical method to model underwater welds in finite element analysis.

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General information
State: Published
Organisations: Nagoya University
Contributors: Chen, X., Kitane, Y.
Publication date: 2010
Peer-reviewed: Yes

Publication information
Journal: Journal of Structural Engineering
Volume: 56A
ISSN (Print): 0733-9445
Ratings:
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 2.27 SJR 1.74 SNIP 1.733
Web of Science (2017): Impact factor 1.903
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 1.91 SJR 1.228 SNIP 1.834
Web of Science (2016): Impact factor 2.021
BFI (2015): BFI-level 2
Experimental study on strength and ductility of underwater fillet welds in repairing offshore steel structures

Underwater wet welding is one of the most common repair measures for corroded offshore steel structures. Few studies have been carried out systematically concerned with mechanical properties of such welds, thus current design provisions rely heavily on limited experimental data on welds made underwater and design properties for corresponding welds made in air. This paper presents a series of experiments on forty-five fillet welded specimens featuring welding both in air and underwater. Weld strength and ductility of fillet welds are examined through strength tests, which are also complemented by Vickers hardness tests and microstructure examination to better understand the weld details. The tested parameters include two welding environments, two weld orientations, two base structural types, and four base steels. Based on the tests, differences between underwater and in-air fillet welds are examined in terms of strength, ductility, and failure modes, underwater weldability of base steels is also evaluated.

General information
State: Published
Organisations: Nagoya University
Contributors: Chen, X., Kitane, Y., Itoh, Y.
Projects:

**Verification of Structural Properties for Bend-Twist Coupled Wind Turbine Blades**
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Branner, K., Main Supervisor, Department of Wind Energy
Bode, J., Supervisor
Chen, X., Supervisor, Department of Wind Energy
Industrial PhD
01/03/2018 → 28/02/2021
Award relations: Verification of Structural Properties for Bend-Twist Coupled Wind Turbine Blades
Project: PhD

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07/11/2017 → …
Project: Research

Activities:

**Structural degradation of a large composite wind turbine blade in a full-scale fatigue test**
Period: 8 Nov 2017
Xiao Chen (Speaker)
Wind Turbines
Department of Wind Energy

Description
Presented at 2nd International Symposium on Multiscale Experimental Mechanics: Multiscale Fatigue
Degree of recognition: International
Documents:
Xiao_Chen_ISMEM2017_3

Related organisation
Structural degradation of a large composite wind turbine blade in a full-scale fatigue test
Chen, X. (Speaker)
8 Nov 2017
Activity: Talks and presentations › Conference presentations