“Fatigue Behavior of Welded Joints in Offshore Steel Structures – Effect of High Frequency Hammer Peening Methods and Corrosion”

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DAAD Deutscher Akademischer Austausch Dienst German Academic Exchange Service
KIT Karlsruhe Institute of Technology
UNIVERSITY OF PATRAS ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΑΤΡΩΝ

Speaker Introduction

Dr.-Ing. Stefanos Gkatzogiannis was born in Veria, Greece in 1989. In 2020, he completed his Doctorate in Engineering (Dr.-Ing.) at the Karlsruhe Institute of Technology (KIT) with *"summa cum laude"*, where he is employed since 2012 at the KIT Steel and Lightweight Structures, Research Center for Steel, Timber and Masonry. He had previously obtained his Diploma in Civil Engineering at the Aristotle University of Thessaloniki (AUTH) selecting a specialization on structural engineering. As a research associate at KIT, Dr. Gkatzogiannis has carried out 4 research projects and has coauthored numerous peer-reviewed journal and conference publications, while he has served as a reviewer for several international journals. His research interests are relevant to the fields of fatigue of metallic structures, corrosion fatigue, FE simulations of welding processes, contact and impact modelling, dynamics of structures etc. For the last two years, Dr. Gkatzogiannis parallel to his academic tasks works as a structural engineering consultant for the German and Greek industry. He speaks Greek, English and German.

Outline

- Offshore Wind Turbines (OWT)
- The problem of corrosion fatigue
- Corrosion fatigue and Offshore Wind Turbines
- High Frequency Mechanical Impact (HFMI)
- HFMI in corrosive environments
- Laboratory tests with accelerated corrosion
- Corrosion fatigue test results of HFMI-treated specimens
- Integration in the production chain of offshore wind turbines
- Possibilities offered by numerical simulation
- Summary

Offshore Wind Turbines

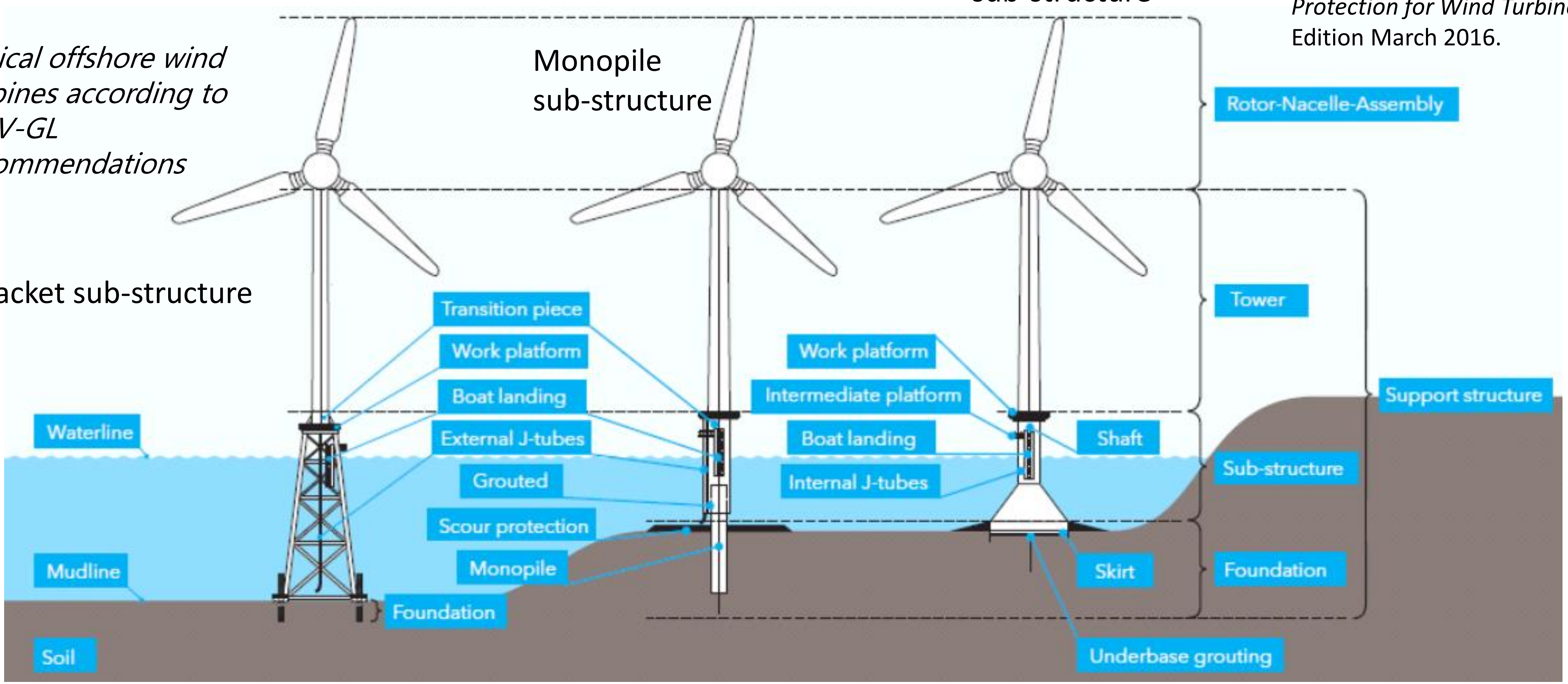
Typical offshore wind turbines according to DNV-GL recommendations

DNVGL-RP-0416; *Corrosion Protection for Wind Turbines*, Edition March 2016.

Jacket sub-structure

Monopile sub-structure

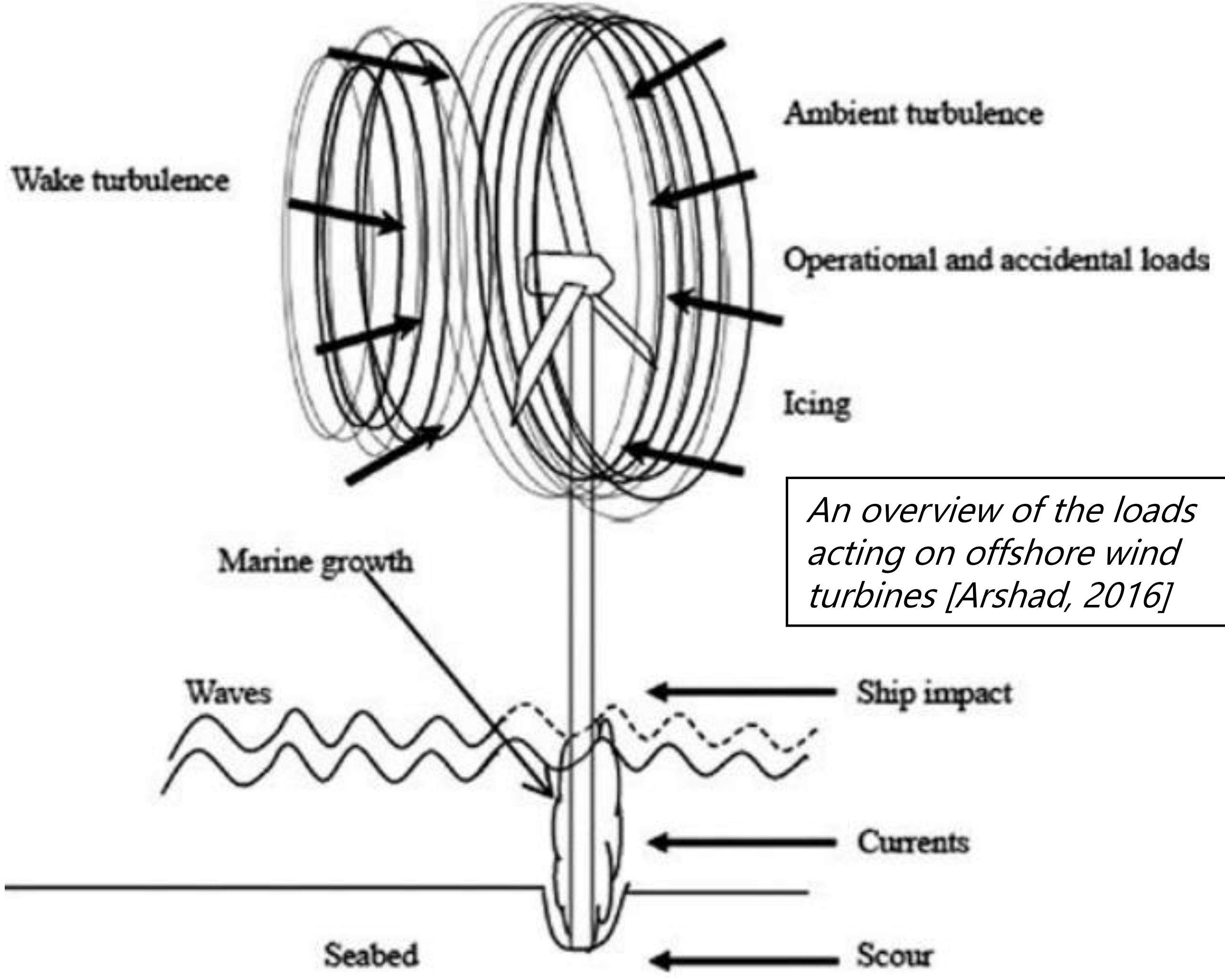
Gravity-based sub-structure



Offshore Wind Turbines

Arshad M., O'Kelly B. C.; Analysis and Design of Monopile Foundations for Offshore Wind-Turbine Structures, *Marine Georesources & Geotechnology* **34**, pp. 503–525, 2016.

- Fatigue loads are applied on the support structures of offshore wind turbines due to simultaneous action of aerodynamic and hydrodynamic loading:
  - Rotor loads (P and 3P)
  - Sea waves (ordinary waves in the range of 0.1 to 1 Hz)
  - Sea currents
- Monopiles and jacket structures are welded and therefore, prone to fatigue loads.
- Fatigue life of the sub-structures is predominant for the structural lifespan of OWTs!
- Nacelle and blades costs constitute merely 15-20 % of the total cost, monopile and tower the remaining 80-85 % - increase of the fatigue life can lead to significant decrease of levelized cost over the lifespan.



An overview of the loads acting on offshore wind turbines [Arshad, 2016]

Offshore Wind Turbines

Welding a monopile
(welder for scale!)

Corrosion fatigue

According to [Suresh, 2004] *„Corrosion-fatigue is a term which is commonly used to denote the damage and failure of a material under the combined action of cyclic stresses and any embrittling medium".*

The degradation of the material caused by corrosion quite often leads to a significant shortening of the structure's fatigue life.

Corrosion not only degrades material and reduces the effective cross section of a steel component but alters the material behavior as well through its influence on the microstructure.

Jacket structures and monopiles are susceptible to fatigue loads as both are welded. Especially in jackets, high stress concentrations are met as well, unless suitable weldment geometries are selected.

Part of a monopile at sea level. Corrosion signs on a coated surface and weld beads can be seen.

Suresh S.; *Fatigue of Materials,* 2nd Edition, Cambridge University Press, Cambridge (UK), 2004.

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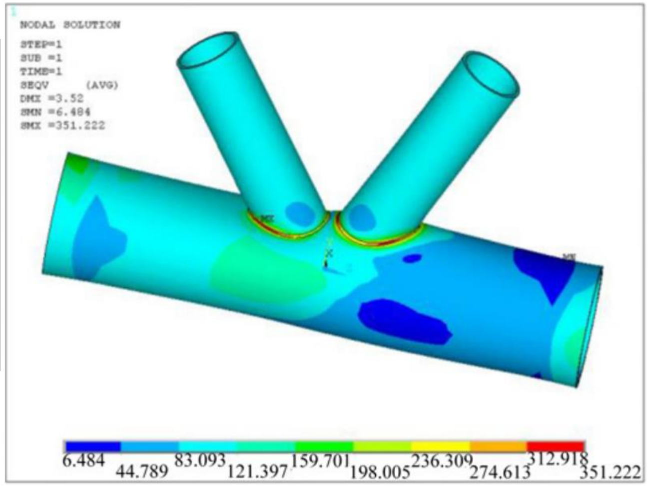
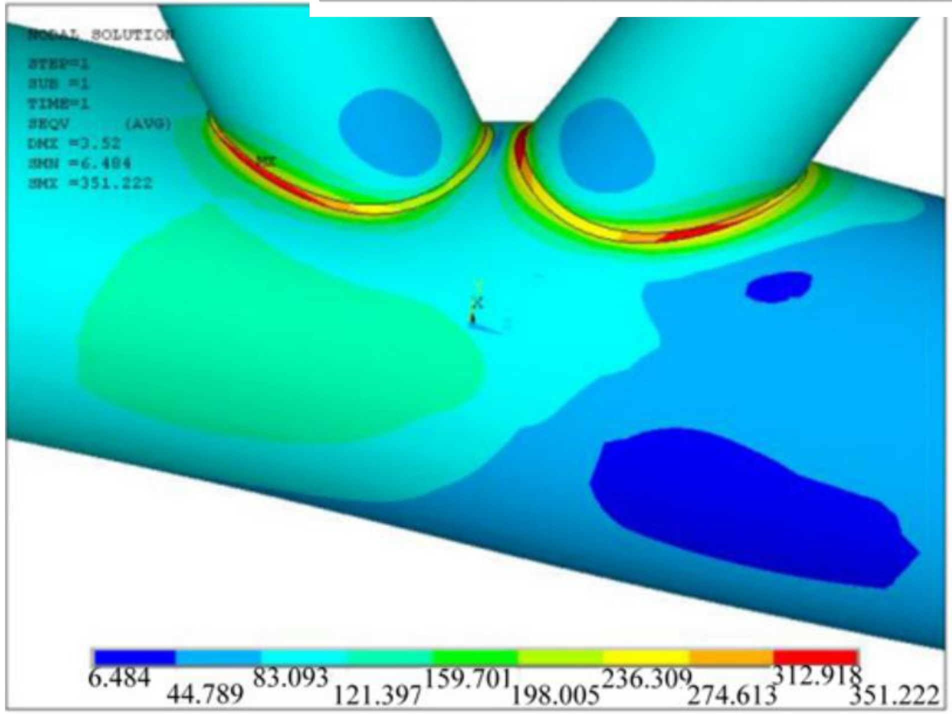
Stress concentration of K-Joints considering the effect of welding residual stresses (material with yield strength of 420 MPa) - Contours of von Misess stress in Mpa [Cao. 2013]



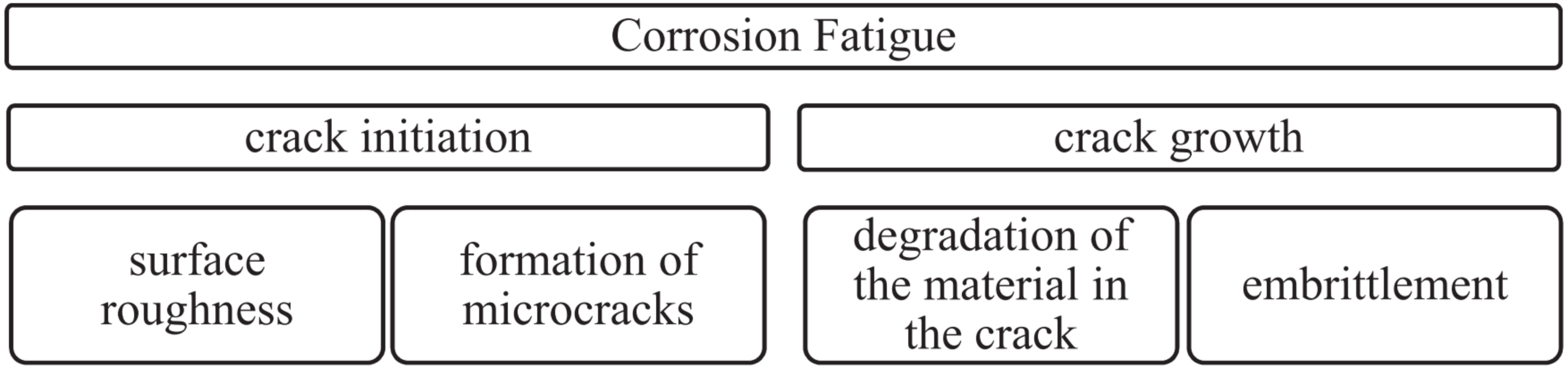


Suresh S.; *Fatigue of Materials,* 2nd Edition, Cambridge University Press, Cambridge (UK), 2004.

Cao Y., Meng Z., Zhang S., Tian H.; FEM Study on the Stress Concentration Factors of K-joints with Welding Residual Stress, *Applied Ocean Research* **43**, pp. 195-205,2013.

Corrosion fatigue

Influence modes of corrosion on the fatigue behavior of steel structures [Gkatzogiannis, 2019]



Corrosion phenomena degrade steel in various ways. The most notable from an engineering point of view are:

- the reduction of cross sections due to material removal
- the surface corrosion: surface roughness is increased, microcracks are created – fatigue crack initiation is accelerated
- the hydrogen embrittlement: the ductility of the material is reduced – especially when cracks are formed, the resistance of the crack tip to crack propagation is reduced due to penetration of the corrosive medium in the crack
- the formation of corrosion pits (pitting corrosion): pits of corrosion are formed, reducing rapidly a section's mechanical resistance

Gkatzogiannis S., Weinert J., Engelhardt I., Knoedel P., Ummenhofer T.; Correlation of Laboratory and Real Marine Corrosion for the Investigation of Corrosion Fatigue Behaviour of Steel Components, *International Journal of Fatigue* **126**, pp. 90-102, 2019.

Corrosion fatigue and OWT

DNVGL-RP-0416; *Corrosion Protection for Wind Turbines*, Edition March 2016.

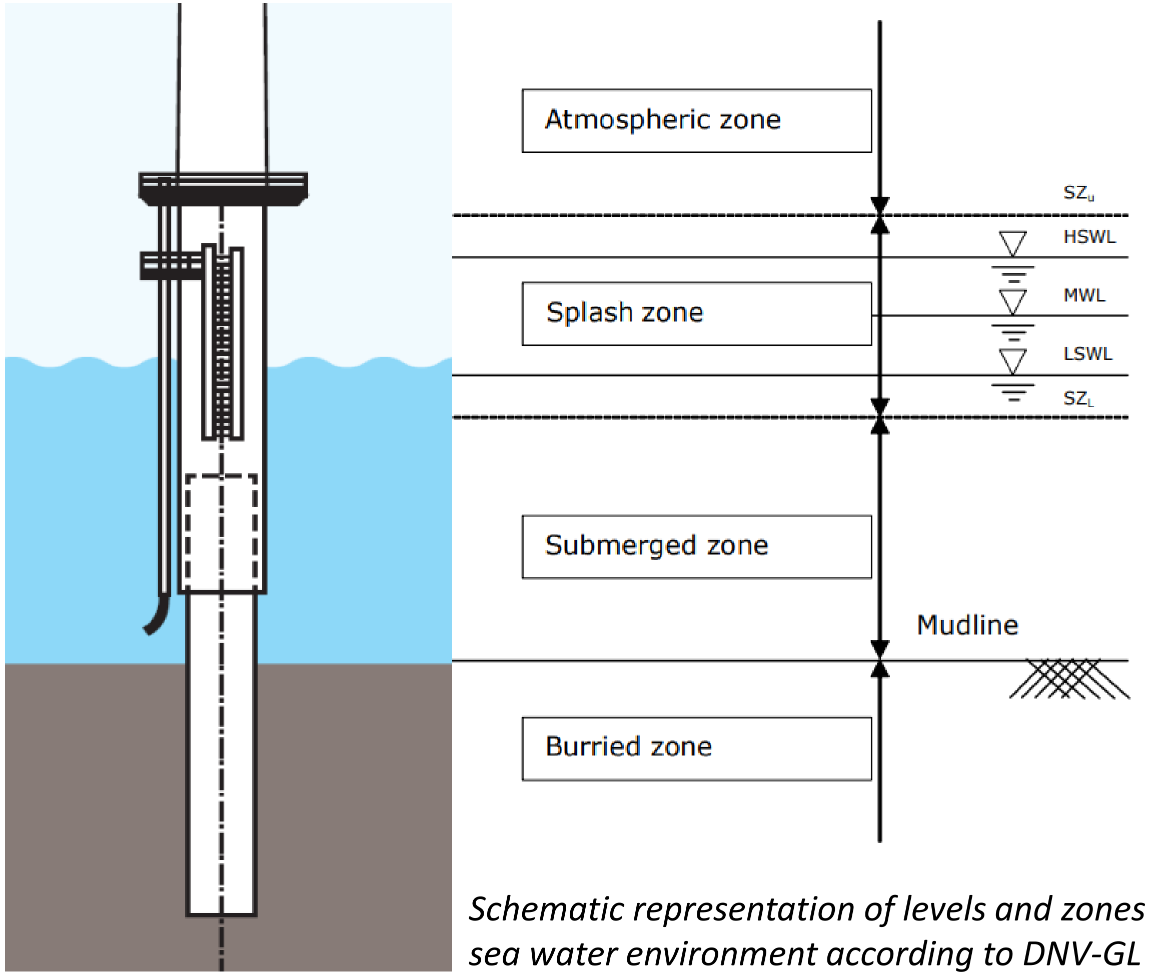
Most common anti-corrosion measure on OWTs is the application of coatings or cathodic protection.

Zones with different corrosion aggressiveness are defined. In the splash zone, where the structure is exposed alternatively to seawater and atmospheric air due to the wave motion and tide:

- the corrosive environment is severe due to the constant alteration of atmospheric air and seawater exposure
- maintenance of corrosion protection is not practical
- cathodic protection is not effective

Corrosion rates of approx. 0.10 mm/year are predicted, while in the splash zone up to 0.40 mm/year [DNVGL-RP-0416].

Either a very conservative design or regular inspections for fatigue cracks are required.



Schematic representation of levels and zones in sea water environment according to DNV-GL recommendations

High Frequency Mechanical Impact (HFMI)

High Frequency Mechanical Impact (HFMI) refers to a group of post-weld hammer treatment methods. Amongst others:

- the Ultrasonic Impact Treatment (UIT)
- the High Frequency Impact Treatment (HiFIT)
- the Pneumatic Impact Treatment (PIT)

The application of HFMI leads to a significant enhancement of the weldments' fatigue life.

The main principle of HFMI is common for all the relevant methods and includes the impact treatment (hammering) of the welded joints by a craftsman handling a device that accelerates one or more pins made of hard steel towards the weld toe.

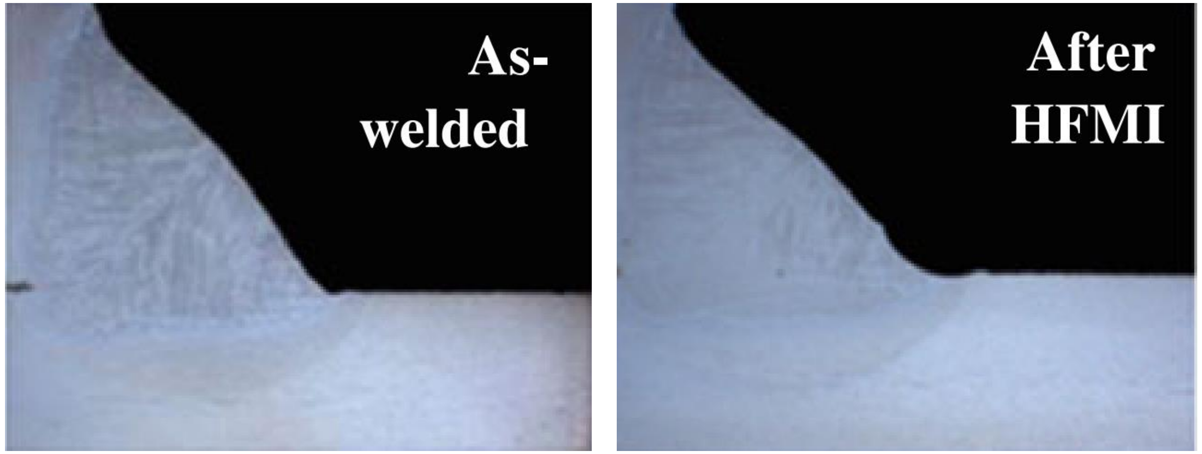
HFMI treatment of a fillet weld [Gkatzogiannis S., Doctoral Examination]

Gkatzogiannis S.; *Finite Element Simulation of Residual Stresses from Welding and High Frequency Hammer Peening*, Doctoral Examination, KIT Department of Civil Engineering, Geo and Environmental Sciences, 10/06/2020.

High Frequency Mechanical Impact (HFMI)

Through the hammering, the weld toe is plastically deformed, the geometrical weld notch effect is reduced and compressive residual stresses (RS), which counterbalance the detrimental tensile WRS, are introduced in the treated area. Increased hardness is documented for the surface layers of the treated area.

Macrosections of as-welded and HFMI-treated weldments



Marquis G. B., Barsoum Z.; *IIW Recommendations for the HFMI Treatment – For Improving the Fatigue Strength of Welded Joints*, 1st Edition, Springer Singapore (IIW Collection), Singapore, 2016.

HFMI trace

Gkatzogiannis S.; *Finite Element Simulation of Residual Stresses from Welding and High Frequency Hammer Peening*, Doctoral Examination, KIT Department of Civil Engineering, Geo and Environmental Sciences, 10/06/2020.

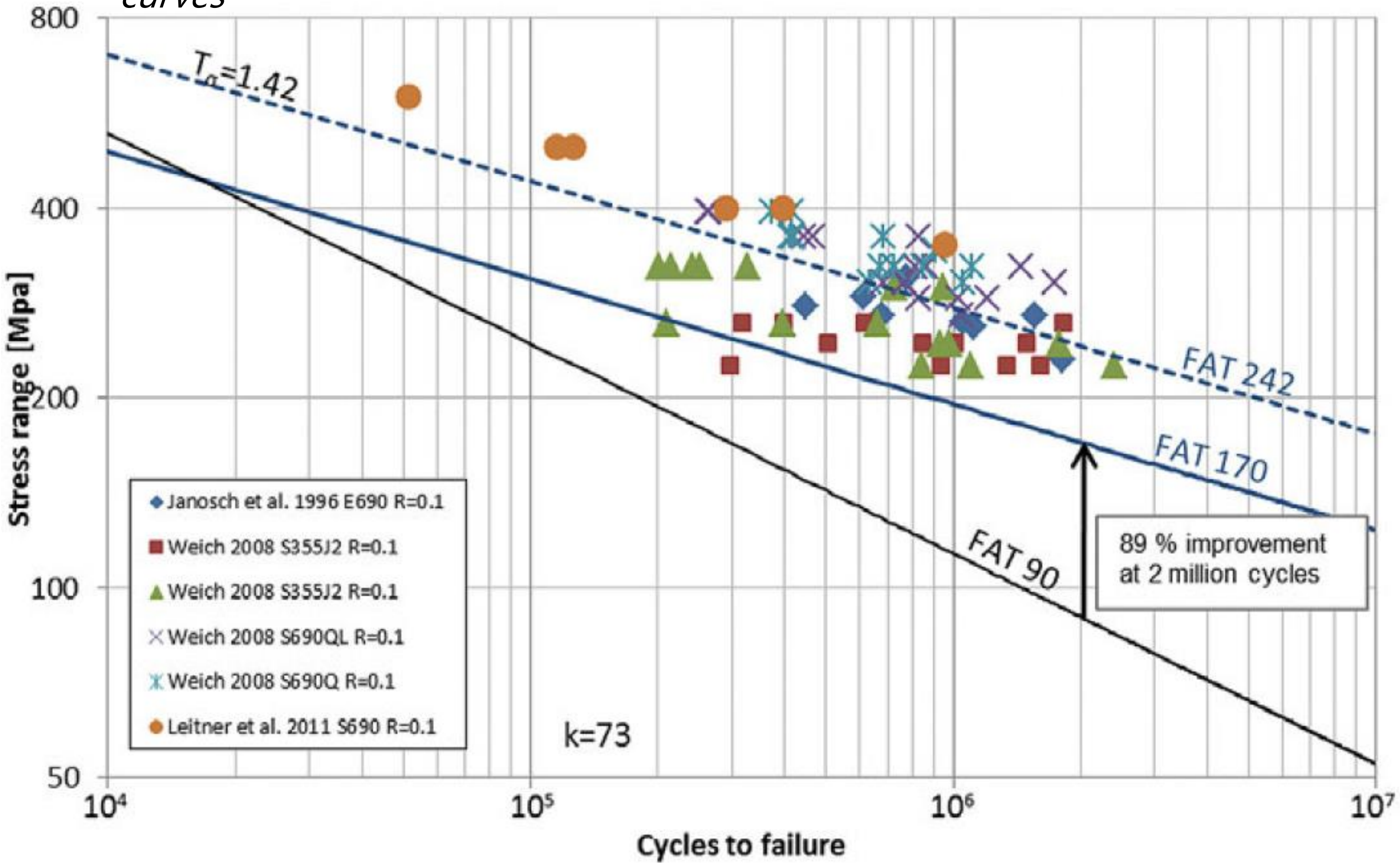
High Frequency Mechanical Impact (HFMI)

Until recently, validation of HFMI's eficciency was based on phenomenological investigations:

- extensive experimental investigations in the last two decades verified empirically the method's efficiency
- tests mostly on HFMI-treated small fatigue test specimens for various materials, geometries and wall thicknesses
- fatigue strength enhancement of more than 100 %, increase of fatigue life in the high cycle fatigue regime of more than 10 times
- fatigue strength (FAT Classes) improvement factors have been proposed / set the background for the establishment of design codes for the application of HFMI [IIW Recommendations, 2016], [DASt Guideline 026, 2019] (see Dr. Weidner's presentation)

Evaluation of experimental results from several sources and recommended FAT curves

Yildirim H. C., Marquis G. B.; *Welding in the World* **56** (7-8), pp. 82-96, 2013.



HFMI in corrosive environments

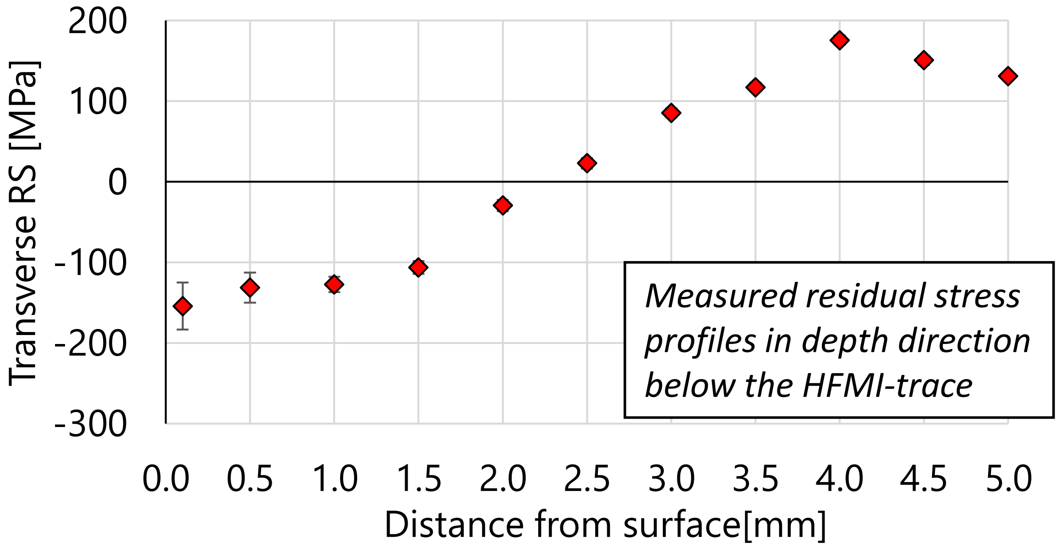
Application of HFMI on OWTs shows great potential:

- low cost, great benefit
- reproducibility
- straightforwardness

Questions arise though, due to possible influence of corrosion on the effectiveness of the method. Degradation of the material's upper surface layers for instance, could lead to a relaxation of the introduced beneficial compressive residual stresses.

Residual stress measurements carried out with a neutron diffractometer have shown that significant compressive stress are met even in a depth of 1.5 mm below surface [Schubnell, 2020].

Residual stress measurements on HFMI-treated fillet welds with a neutron diffractometer



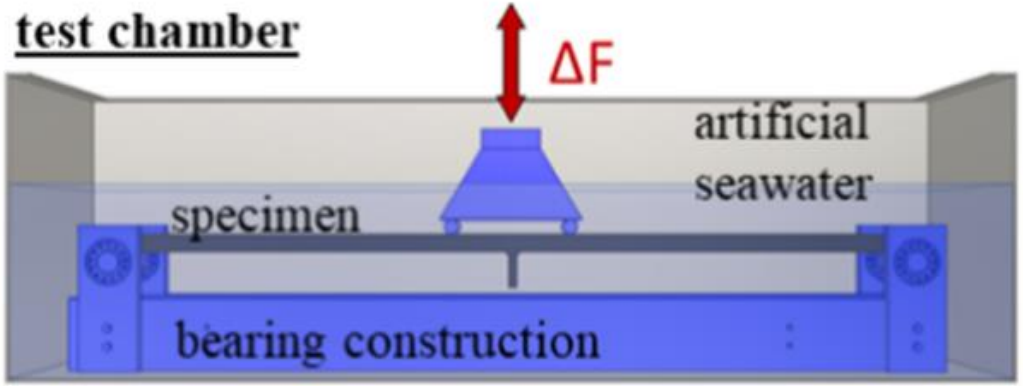
Schubnell J., Carl E., Farajian M., Gkatzogiannis S., Knödel P., Ummenhofer T., Wimpory R., Eslami H.; Residual Stress Relaxation in HFMI-Treated Fillet Welds After Single Overload Peaks, *Welding in the World* **64,** pp. 1107–1117, 2020.

Laboratory tests with accelerated corrosion

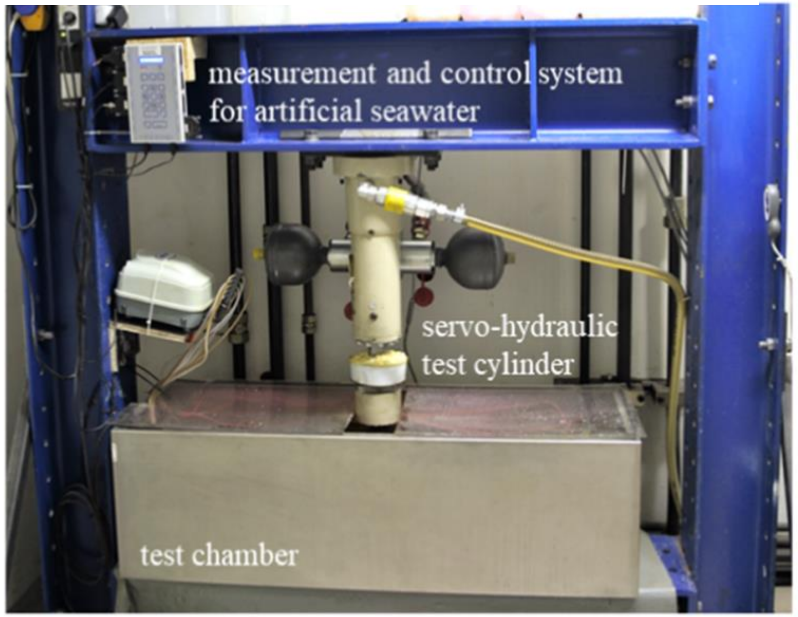
In order to test the efficiency of HFMI in corrosive environments, a research project, containing extensive experimental investigations was carried out [Ummenhofer, 2018].

Corrosion was simulated in the laboratory with

- Salt spray chamber tests [ISO 9227:2017] – sequential corrosion
- Artificial seawater [ASTM D1141-98] – simultaneous corrosion
- Electrolysis – first application



4-point bending tests in artificial seawater



Ummenhofer T., Engelhardt I., Knödel P., Gkatzogiannis S., Weinert J., Loeschner D.; *Erhöhung der Ermüdungsfestigkeit von Offshore-Windenergieanlagen durch Schweißnahtnachbehandlung unter Berücksichtigung des Korrosionseinflusses (Increasing the Fatigue Strength of Offshore Wind Turbines through Post-Weld Treatment under Consideration of the Corrosion Influence)*, Abschlussbericht DVS 09069 – IGF 18457 N, 2018.

ISO 9227:2017; *Corrosion Tests in Artificial Atmospheres — Salt Spray Tests*, 4th Edition, 2017.

ASTM D1141-98, *Standard Practice for the Preparation of Substitute Ocean Water*, 2013.

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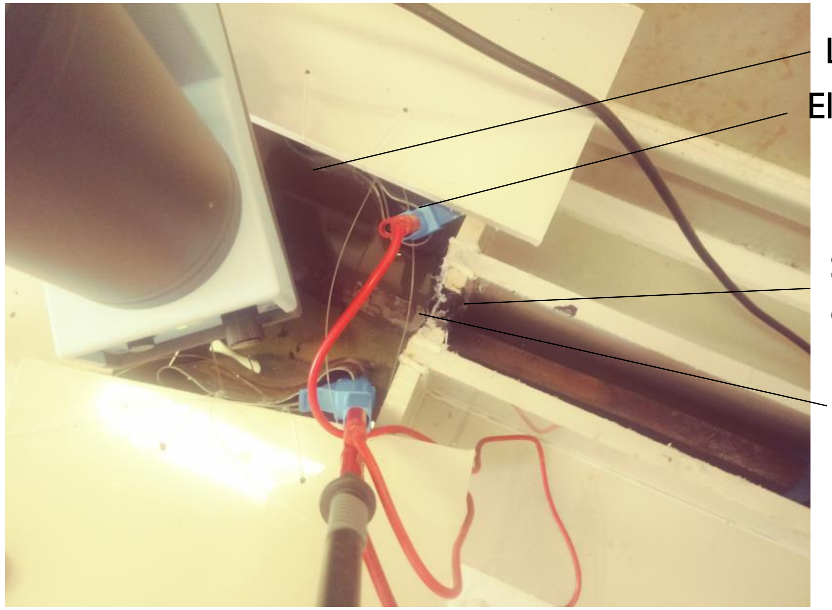
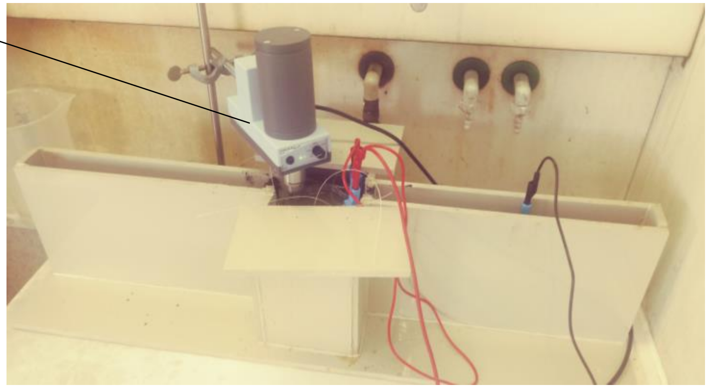


Electrolytic setup



Ummenhofer T., Engelhardt I., Knödel P., Gkatzogiannis S., Weinert J., Loeschner D.; *Erhöhung der Ermüdungsfestigkeit von Offshore-Windenergieanlagen durch Schweißnahtnachbehandlung unter Berücksichtigung des Korrosionseinflusses (Increasing the Fatigue Strength of Offshore Wind Turbines through Post-Weld Treatment under Consideration of the Corrosion Influence)*, Abschlussbericht DVS 09069 – IGF 18457 N, 2018.

ISO 9227:2017; *Corrosion Tests in Artificial Atmospheres — Salt Spray Tests*, 4th Edition, 2017.

ASTM D1141-98, *Standard Practice for the Preparation of Substitute Ocean Water*, 2013.

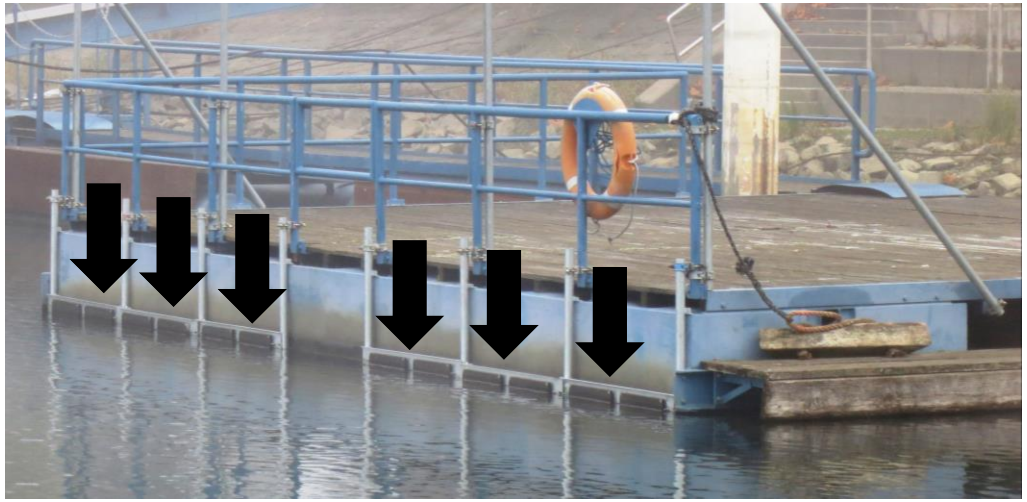
Laboratory tests with accelerated corrosion

Correlation of laboratory corrosion duration with corrosion duration in real marine environment was carried out based on measurements of specimens corroded in the harbor area of Kiel (Baltic sea) in the framework of a previous project.

Correlation was based on:

- optical inspection
- roughness measurements
- thickness loss
- fatigue strength reduction of as-welded specimens

Deposition of specimens in the splash zone in the harbor of Kiel

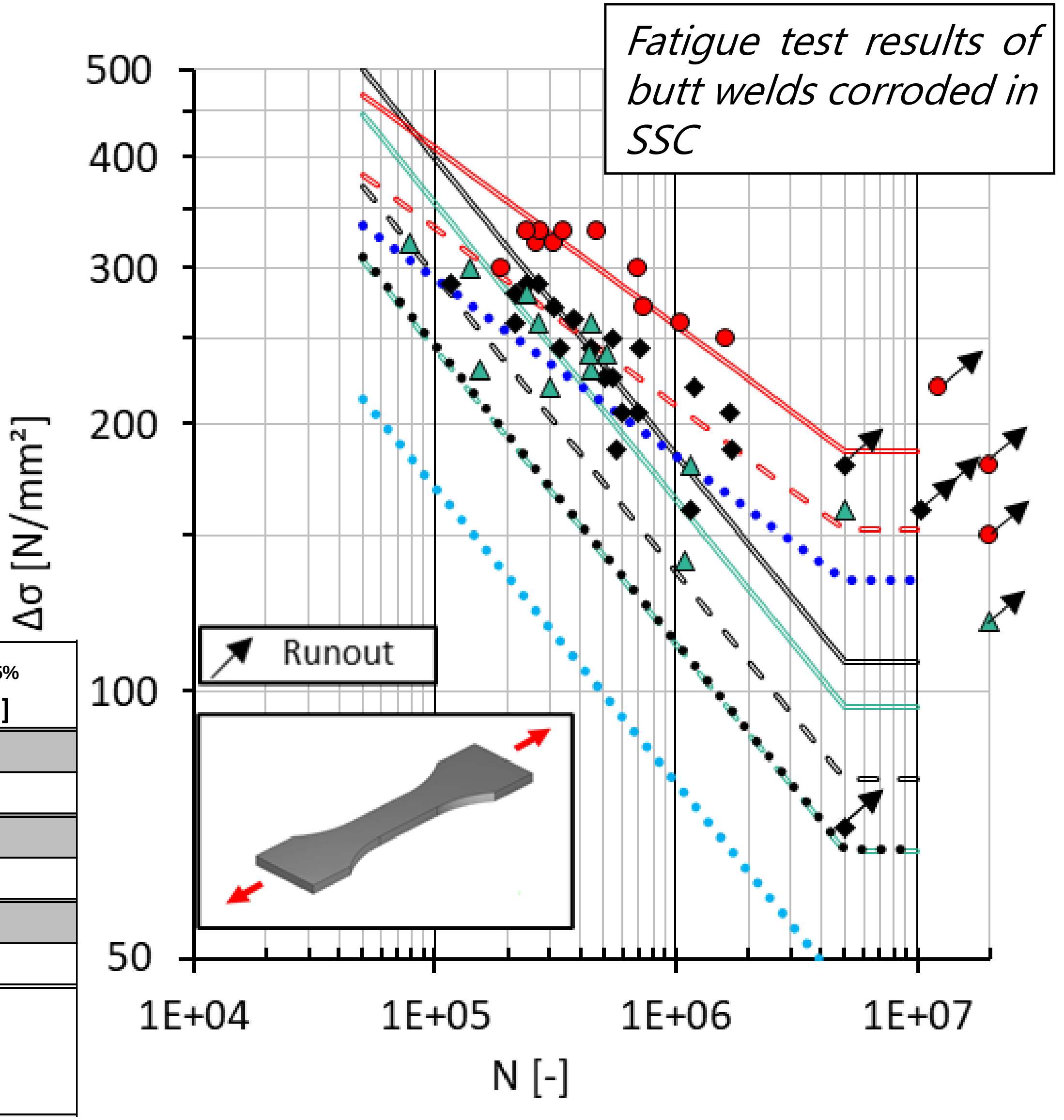


Butt weld corroded in the laboratory for 12 days (left) and specimen of parent material corroded for 2 years at the sea (right)

Fatigue test results

Fatigue tests on the corroded specimens have shown that for laboratory corrosion corresponding to 6 months in real marine conditions a significant fatigue strength enhancement through HFMI is achieved. The influence of laboratory corrosion when comparing as-welded uncorroded and corroded specimens is becoming evident.

These first results show, that coating damages that leave the HFMI-treated welds unprotected, cannot reduce the effectivity of HFMI for a significant period (inspection intervals).



Symbol	Test Series	m [-]		$\Delta\sigma_{c,50\%}$ [MPa]	$\Delta\sigma_{c,95\%}$ [MPa]
◆	BW_AW_uncor_ax	free	3.5	157	123
		fixed	3.0	146	108
▲	BW_AW_SSC_ax	free	2.9	128	87
		fixed	3.0	130	89
●	BW_HFMI_SSC_ax	free	5.4	229	191
		fixed	5.0	224	182
···········	EC Detail Category 90	3.0		90	
···········	IIW - HFMI	5.0		160	
···········	DNVGL - D	3.0		62	

BW: butt weld AW: as welded SSC: salt spray chamber ax: axial tests

Integration in the production chain of OWT

Prior to the integration of HFMI in the production chain of OWTs, open questions must be clarified :

- do surface preparation treatments influence the stability of the compressive residual stress field introduced by HFMI? – common manufacturing practice of OWTs dictates shot blasting of the surface to achieve sufficient adhesion of coatings (see DNVGL-RP-0416, ISO 8501-1)
- are the coatings' adhesivity and mechanical performance in the deep HFMI trace sufficient?

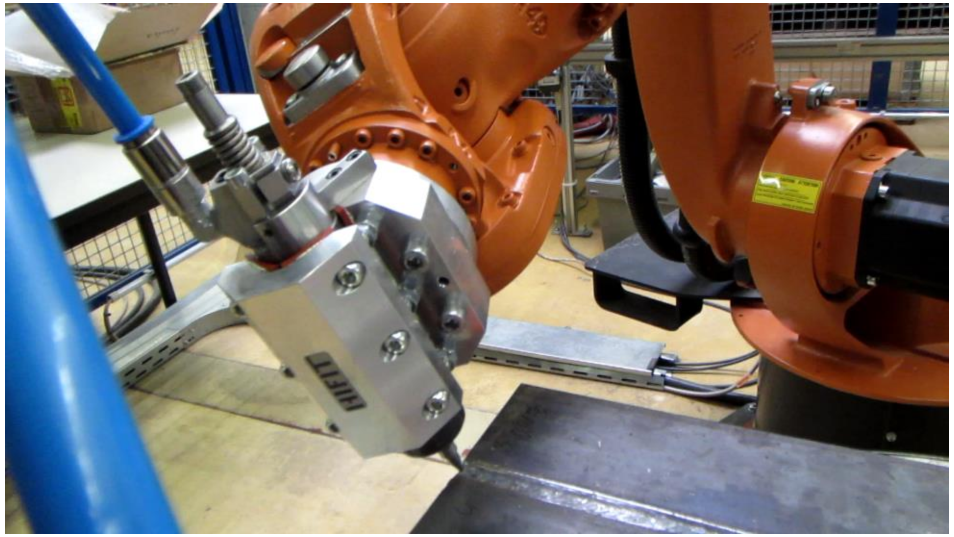
These two points are currently investigated [Ummenhofer, 2021].

Automation of HFMI similarly to robotic welding is currently under development and could further reduce manufacturing costs.

Recently validated numerical models of HFMI provide a different insight to the method.

Shot blasting of pipe's outer surface for the application of coating

Robotic HiFIT treatment of a butt weld, courtesy of Mr. Neher and HiFIT GmbH



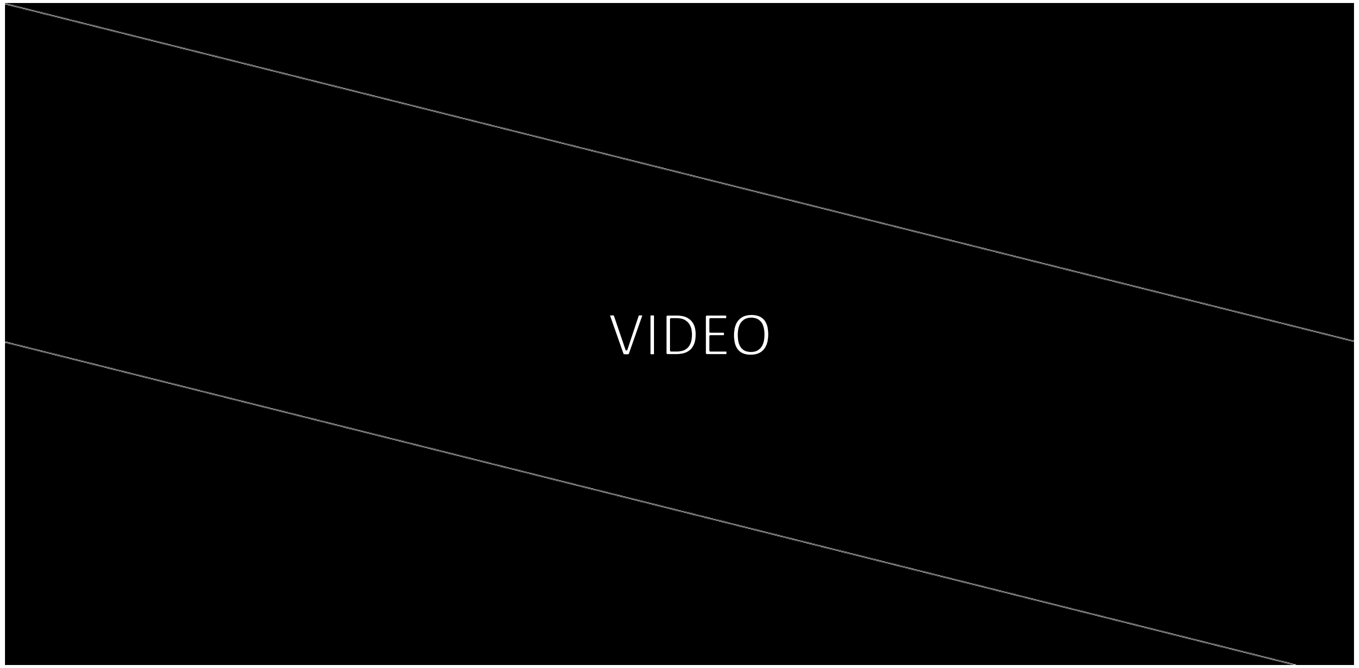
Ummenhofer T., Engelhardt I., Weidner P., Gkatzogiannis S., Weinert J., Hadziahmetovic D., Löschner D.; *Absicherung Der Prozesskette Zur Anwendung Höherfrequenter Hämmerverfahren Bei Offshore-windenergieanlage*, (Laufendes Forschungsprojekt), FOSTA P 1454– IGF 21382 N, 2021.

Possibilities offered by numerical simulation

Validated numerical models for the simulation of HFMI have been presented in the last years (see [Gkatzogiannis, 2020], [Schubnell, 2021]).

FE simulation of HFMI offers us a different insight regarding the material behavior in comparison to the phenomenological ones – coupled with weld simulation, it can estimate with satisfying accuracy the residual stress state.

The depth of the residual stresses and the fatigue strength enhancement is estimated for different geometries, thicknesses and HFMI treatment parameters, avoiding numerous costly experimental investigations (residual stress measurements and fatigue tests).



HFMI treatment of a parent material specimen of S355, contours of von Mises stresses, [Gkatzogiannis, Doctoral Examination, 10/06/2020]

Gkatzogiannis S.; *Finite Element Simulation of Residual Stresses from Welding and High Frequency Hammer Peening*, Doctoral Dissertation, Department of Civil Engineering, Geo and Environmental Sciences, Karlsruhe Institute of Technology, 2020.

Schubnell J.; *Experimentelle und numerische Untersuchung des Ermüdungsverhaltens von verfestigten Kerben und Schweißverbindungen nach dem Hochfrequenzhämmern, Dissertation*, KIT-Fakultät für Maschinenbau, Karlsruhe, 2021.

To summarize…

- Fatigue strength is predominant for the structural durability and therefore, the design of OWTs. Due to simultaneous influence of the aggressive corrosive marine environment, especially at the splash zone of the OWTs, the corrosion fatigue problem becomes crucial.
- The High Frequency Mechanical Impact (HFMI) shows potential for extending significantly the fatigue life of OWTs. Its efficiency has been validated in the past two decades based on extensive experimental investigations, which led to its integration in structural design recommendations.
- The corrosion fatigue resistance of HFMI-treated specimens for short-duration exposure to corrosion has been validated. Potential damages on coatings cannot influence the efficiency of HFMI for extending the fatigue life of weldments, when no significant material removal takes place.
- Prior to an application on the weldments of OWTs though, some further effects should be investigated/clarified:
  - For the integration of HFMI in the production chain of OWTs it must be ensured that the subsequent shot blasting of the surface, necessary for achieving sufficient adhesiveness of the coating, does not destabilize the compressive residual stresses introduced by HFMI.
  - The adhesiveness of coatings in the HFMI trace should be ensured.
- Automatization of HFMI and the simulation of the method with numerical models offer new possibilities regarding the design of HFMI-treated structures, future research and productivity during manufacturing.

Thank you very much for your kind attention!