Abstract - presented at EUROCORR 2020

Customized testing of bolted connections for large subsea wind structures

by Mikkel Østergaard Hansen, Troels Mathiesen (FORCE Technology) and Jens Schiersing Thomsen (SiemensGamesa)

Bolted connections for large subsea wind structures can potentially provide large cost savings by industrializing the manufacturing process and using several sub-suppliers. However, fully welded structures are usually preferred for such applications today due to conservatism and scepticism within the industry about the durability of bolted connections in the submerged and the splash zones. To overcome such challenges and scepticism, a series of customised tests have been developed and performed as part of the research project, CeJacket. The tests address the risk of corrosion and hydrogen embrittlement of carbon steel bolts receiving cathodic protection (CP) in the submerged zone and the risk of corrosion of stainless steel bolts used in the splash zone.

As a basis 8.8 electrogalvanized steel bolts are used in the submerged zone together with protective coatings of the joined steel parts. The applied coatings include both epoxy coatings and metallizing. By using a model setup of the flange joint, short and long-term testing up to 28 weeks has been performed in artificial seawater representing North Sea conditions at different cathodic protection potentials. It is shown that the bolts are well protected on all surfaces including areas that might be shielded from CP in the event of complete depletion of the metallizing coating on flange faces. It is also shown that depletion of the metallizing is negligible even at potentials close the protection limit (-0.8V Ag/AgCl/seawater).

Long-term testing in the splash zone involved simulation of tidal variations, including water splash, dry periods and full submersion periods with CP. The tested stainless steel bolts (EN 1.4435) did not show any signs of degradation after 23 weeks exposure.

The presented work is part of the research project CeJacket, co-funded by Innovation Fund Denmark. The partners in CeJacket project include Bladt Industries A/S, FORCE Technology, SiemensGamesa A/S, Ørsted A/S and Aalborg University.

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Customised testing of bolted connection for large subsea wind structures

Outline

- **Motivation for developing test**
- **Challenges using bolting subsea and in splash zone**
- **Development of tests and results**

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Project partners

SIEMENS Gamesa RENEWABLE ENERGY

Ørsted

BLADT

AALBORG UNIVERSITET

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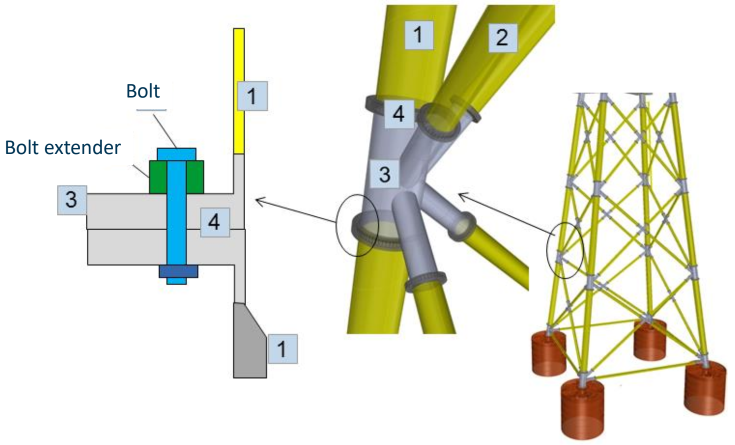
Motivation – R&D project on bolted jackets

CeJacket project:

- **Reduce the cost of producing off-shore wind energy**
- How - Jackets made from pre-coated line pipe with durable FBE coatings = **Cost savings**
  Nodes and tube elements of bracings and legs will ideally be assembled with bolted joints as flange connections



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Challenges in using bolting subsea and in the splash zone

- Must last entire lifetime
- Special fatigue considerations

Special bolt extenders to ensure min. clamping length 10 times the bolt diameter

- Limited possibility for retightening (unwanted and expensive)
- Corrosion
  - Design protection potential below - 0.80 V relative to the Ag/AgCl/seawater reference electrode
- Consider risk of HISC with CP
  - HV requirements – maximum of 350 HV (DNVGL-RP-B401). Only 8.8 bolts meet this
  - Over-protection below -1.15 V relative to the Ag/AgCl/seawater
  - Galvanic anodes preferred over ICCP
- Strict QA/QC requirements to bolts
- Corrosion Resistant Alloys bolting in splash zone
  - Guidelines and standards are not consistent (i.e. ISO 21457, DNVGL-RP-0476). Should include closer description of region, temperature, salinity etc.
  - 1.4401 is already used for smaller parts on foundations, boat-landings etc. in North Sea

Clamp installation on oil rig. Source: ing.dk

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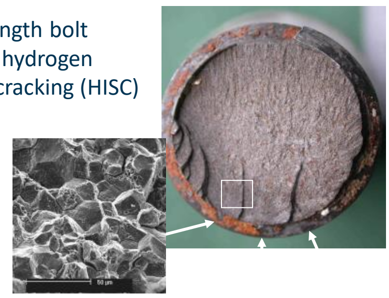
Failures related to subsea bolting

Stainless bolt suffering corrosion fatigue due to poor tightening

High-strength bolt suffering hydrogen induced cracking (HISC)



Insufficient alloy grade and poor heat treatment

intergranular corrosion and fracture

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Subsea and splash zone – Different concepts for bolted connections

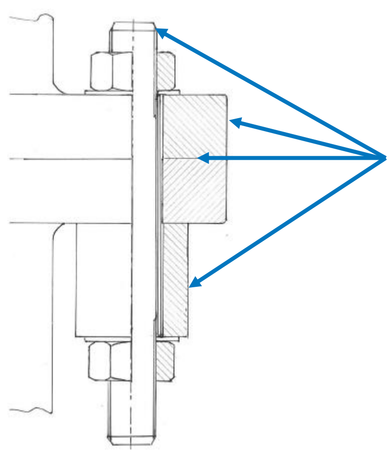
- **Bolts**:

  Submerged: Carbon steel 8.8 bolts with CP and temporary corrosion protection

  Splash zone: Stainless steel 8.8 bolts

- **Other parts:**

  Parts to be coated (organic, TSM and combinations)



Different protective surface treatments. Always TSM on flange surface

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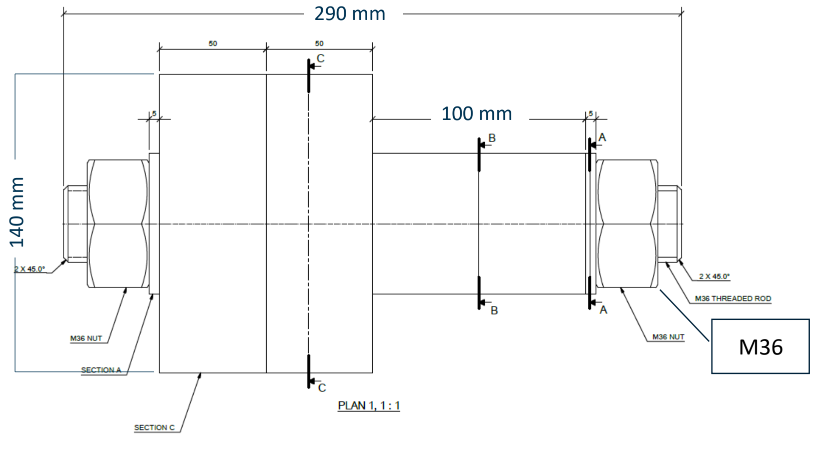
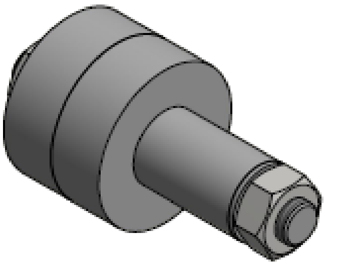
Development of tests – Bolted flange test specimen

- For testing this bolted model flange setup was used





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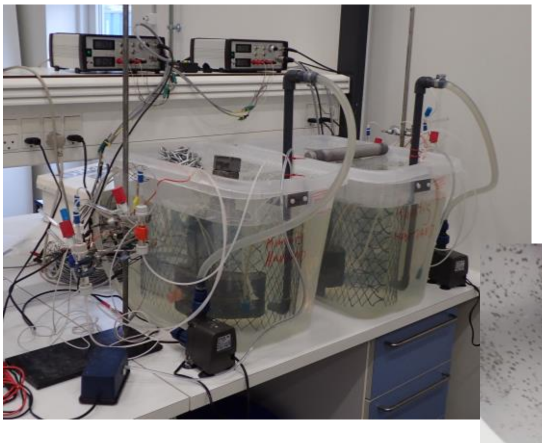
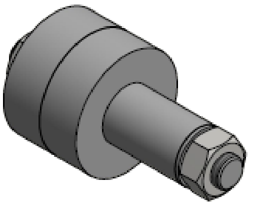
Gap test – Can CP protect flanges with a 200 µm gap?





Potential measured at two depths in gap
- at bolt 52mm from outer edge
- mid of gap 26mm from outer edge

25 °C
Artificial seawater ASTM D1141
Circulation and aeration
Potentiostatic control

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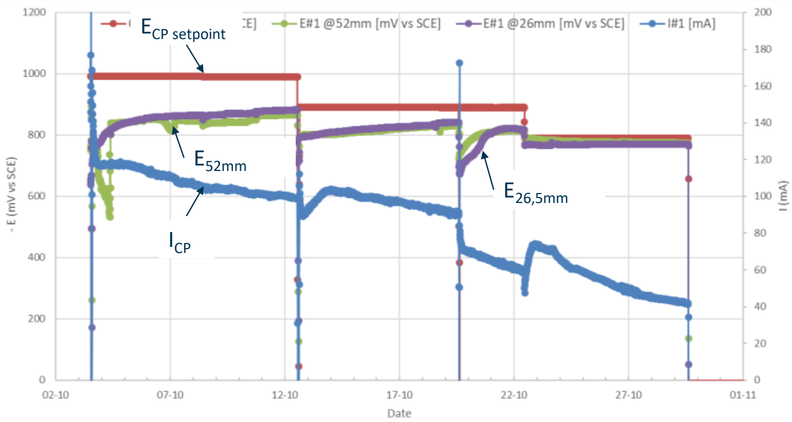
Gap test – Results



Summary of test. All values reported as V vs Ag/AgCl/seaw.					
	Econtrol vs Ag/AgCl/seaw.	Test specimen #1 Min. potential		Test specimen #2 Min. potential	
		@26mm	@52 mm (bolt)	@26mm	@52 mm (bolt)
0-9 days	-1.00 V	-0.89 V	-0.88 V	-0.86 V	-0.88 V
9-19 days	-0.9 V	-0.83 V	-0.82 V	-0.81 V	-0.83 V
19-28 days	-0.8 V	-0.78 V	-0.78 V	-0.78 V	-0.79 V
28-138 days	-0.9 V	-	-	-0.89 V	-0.84 V

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Gap test – Conclusions

- Test set up to produce worst case scenario, including effects of e.g. no surface coating, 200 µm gap, water flow into the gap and prolonged exposure.
- **The test showed good protection of the flange gap, bolts and internal surfaces** of the flange parts and bolt extenders, even in at the minimum criterion for cathodic protection (-0.8 V vs Ag/AgCl/seaw.)
  Supportet upon disassembly of the test specimens.
- The prolonged exposure of test specimen #2 for a further 110 days, **did not show any differences in corrosion** of the inner surfaces of the test specimen assemblies.

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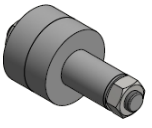
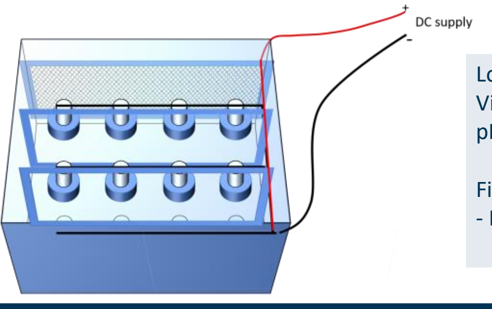
Submerged test of bolted flange – Is the TSM coated flange face protected by CP in combination with different coating configurations of external surfaces, i.e. bolt, nuts and washers.

- The bolts are exposed in artificial seawater while having CP applied at three different potentials





Logging of current and potential
Visual examination
pH measurement

Final evaluation
- Inspect for cracks and corrosion

Applied CP potentials	
	Econtrol vs Ag/AgCl/seawater
0-12 week	-1.05 V
12-18 week	-0.90 V
18-28 week	-0.80 V

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Submerged test of bolted flange

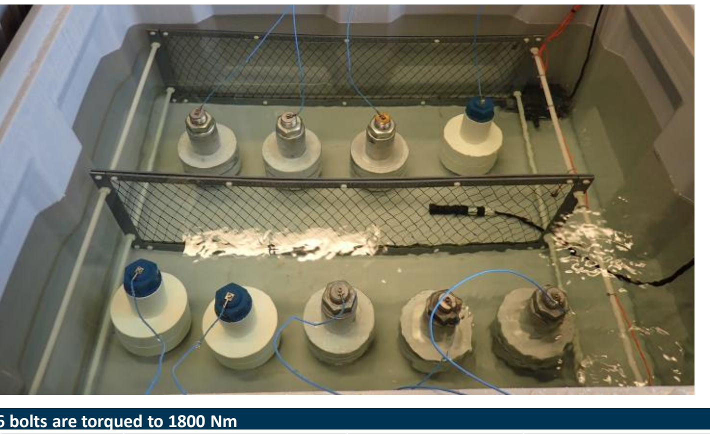

Table 1. Test specimens. M36 bolts are torqued to 1800 Nm

Group no.	ID	Amount	Surface treatment of flange faces	Bolts, nuts and washers	Bolt extender, flange outer side	TSM depletion
T-4	Bolts electroplated zinc	3	TSM (Zn85/Al15) 100 µm	Electroplated zinc	Black	No
T-5	Bolts Xylan	3	TSM (Zn85/Al15) 100 µm	Xylan coating	Hempadur 35560, 600µm (NORSOK 501, 7A system)	No
T-6	Bolts FZV	3	TSM (Zn85/Al15) 100 µm	FZV	Black	No

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Submerged test of bolted flange - Conclusions

- **Calcareous deposits build-up** on the outer surfaces of the test specimens – decrease in currents consumption.
- Water ingress, but the exchange of water is low, **the internal conditions stagnant, air-depleted and non-corrosive**.
- **No cracks** in the stud and nut base metal of the three different types of coated mechanical fasteners
- Superficial corrosion and discoloration on the TSM treated flange surfaces.
  Corrosion depth is shallow – **no depletion of TSM**

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Splash zone test – Behaviour of Bumax 8.8 (high-moly grade of AISI316 stainless steel) and TSM flange coatings in the splash zone in North Sea conditions.

- The test shall evaluate the risk of pitting of the stainless steel, and whether this can affect integrity in 25 years.
- The test shall show if there is a risk of depletion of the TSM coating on the flange face.

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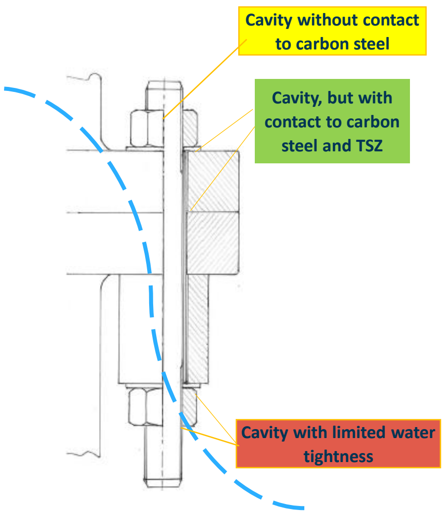
Splash zone test – Factors influencing corrosion of stainless steel in splash zone



Factor	Expected effect on stainless
Cavities	Aggravating – build up local environment
Temperature	Aggravating - facilitates evaporation
Salinity	Aggravating - known [Cl] vs T dependence
pH	Aggravating – if low pH develops in cavity
Wind	Mitigating – decreases time of wetness
Wave action	Mitigating – flushes off micro cells**
Occasional CP	Mitigating – resets localized corrosion, builds up calcareous products
Biology	Both ways
Orientation	Vertical worst
Dissolved oxygen	None
UV	None **

**Strong effect on coated steel flange

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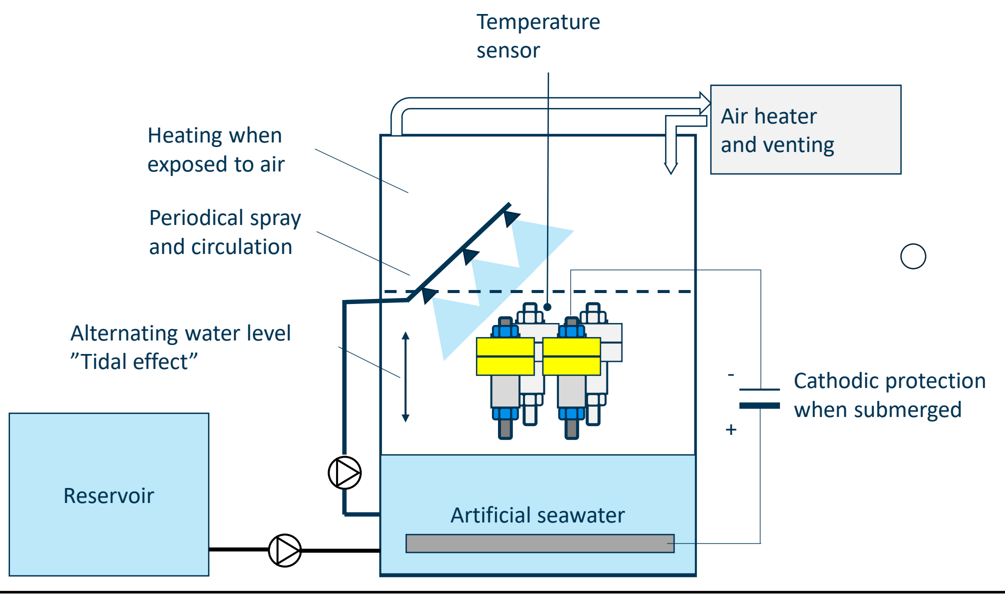
Splash-zone testing of CRA bolting alloys



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Test cycle for worst case exposure conditions in splash/tidal zone

North Sea conditions, ~ 3.5% NaCl, tidal period ~12 hrs, max. period with direct sunlight 3 hrs

Exposure scenario	Test (splash + CP)
Submerged -wave action under submersion	0.5 hrs Submerged Polarised to -1.05V, -0.9V and -0.8V
Splash zone -frequent splashes (10s period)	0.5 hrs
Atmospheric - 1 - calm - sunny and dry	3 hrs Heating to 25°C on surface Venting No CP

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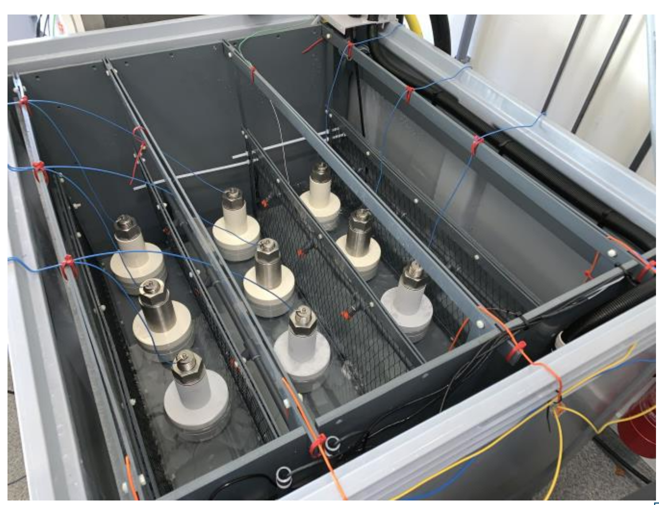
Developed test-concept



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Splash zone test – specimens and results

Test specimens. M36 bolts are torqued to 1800 Nmd							
Group no.	**ID**	**Amount**	**Surface treatment of flange faces**	**Bolts, nuts and washers**	**Bolt extender, flange outer side**	**TSM depletion**	**Corrosion and cracking of bolts**
T1	T1-A T1-B T1-C	3	TSM (Zn85/Al15) 100 µm	Stainless steel BUMAX 8.8	Carbon steel coated with Hempadur 35560, 600µm (NORSOK 501, 7A system) on bolt extender and flanges	**No**	**No**
T2	T2-A T2-B T2-C	3	TSM (Zn85/Al15) 100 µm	Stainless steel BUMAX 8.8	Stainless steel Bolt Extender, Hempadur 35560, 600µm (NORSOK 501, 7A system) on flanges	**No**	**No**
T3	T3-A T3-B T3-C	3	TSM (Zn85/Al15) 100 µm	Stainless steel BUMAX 8.8	TSA (100%Al) on inside and outside of bolt extender + TSA on flange	**No**	**No**

Applied potentials and exposure time	
Exposure time	**Econtrol vs Ag/AgCl/seawater**
0-10 week	-1.05 V
10-16 week	-0.90 V
16-23 week	-0.80 V

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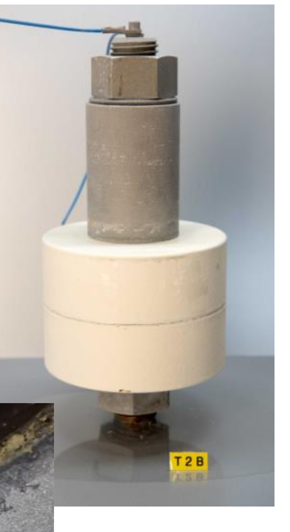
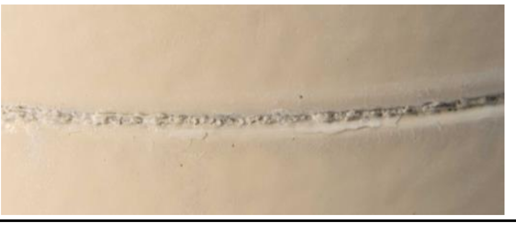
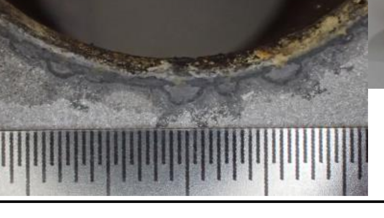
Splash zone test of bolted flange - Conclusions

- After an initial stabilisation period, **calcareous deposits build-up on the outer surfaces** of the test specimens with a resulting decrease in currents consumption.
- For the different material combinations tested, **no pitting, crevice corrosion or cracks** in stud and nut base of stainless BUMAX 8.8 fasteners and stainless bolt extenders
- Superficial corrosion and discoloration were observed on the TSM treated flange surfaces, with some variation in affected area.
  Corrosion depth is shallow – No depletion







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Conclusions

- **Development of new design requires thorough evaluation of standards and customized testing**
- **Development of specialized tests for bolted connections in splash zone and fully submerged has been developed**
- **Testing have been conducted successfully producing relevant data for final design of bolted connections**
- **Test methods show potential for further development to cover sub-tropical and tropical conditions.**

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Thank you for your attention !

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