Monopiles in sand under cyclic loading: the impact of stress-level and loading directionality

Danish Geotechnical Society Seminar: Geotechnical aspects of cyclic loading for offshore wind – the next frontier
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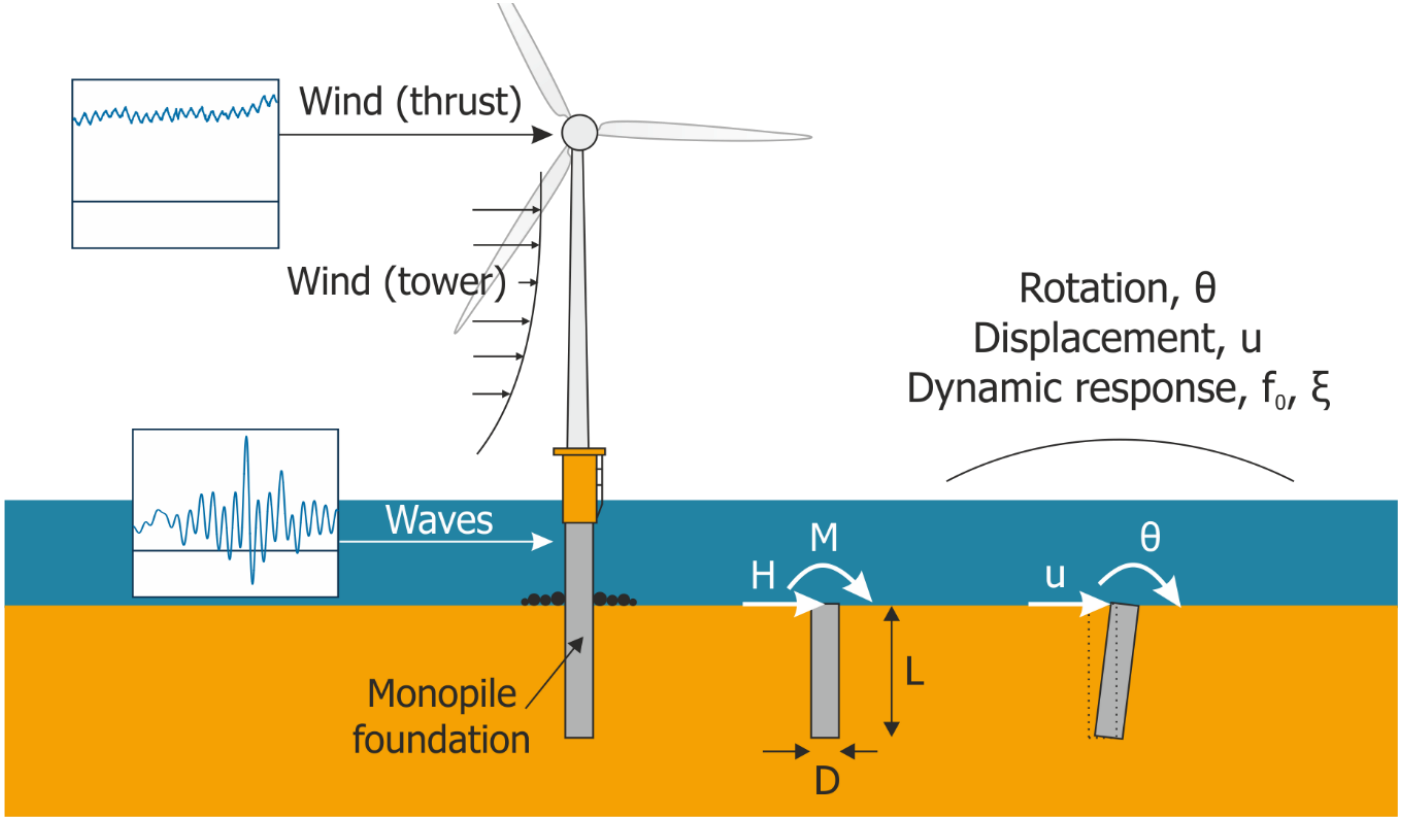
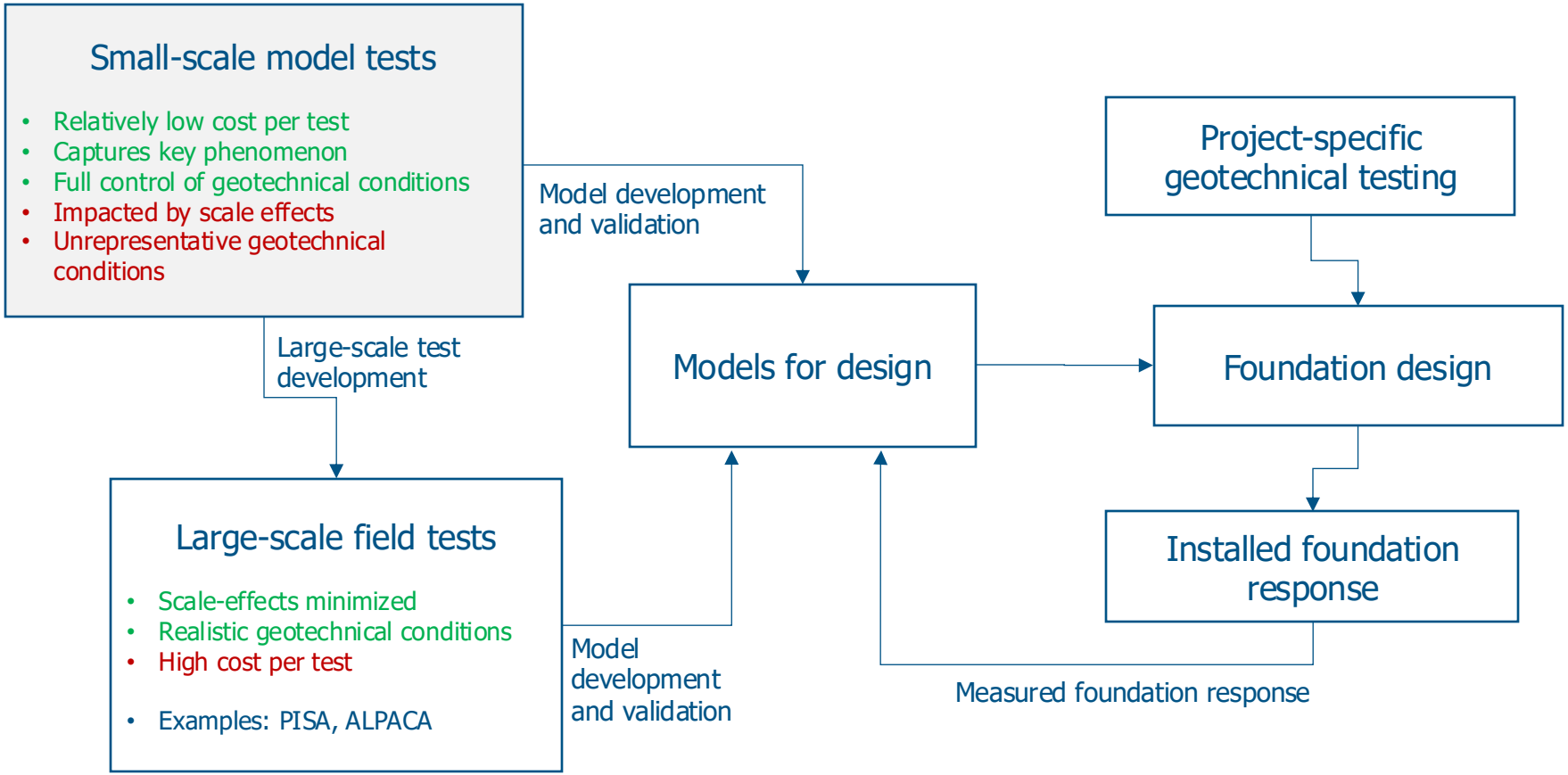
Motivation


Wind (thrust)
Wind (tower)
Rotation, θ
Displacement, u
Dynamic response, f_0, ξ
Waves
M
H
θ
u
L
D
Monopile
foundation

Why perform small-scale model tests?

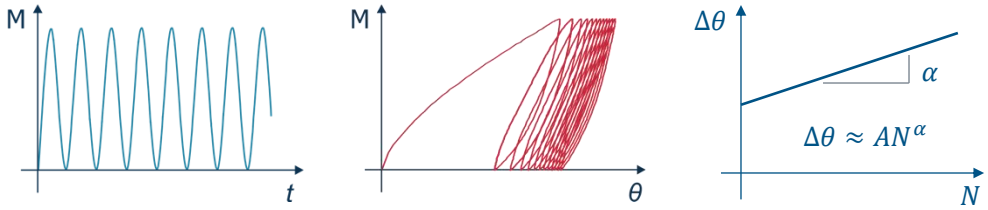


Why perform small-scale model tests?

Small-scale model tests

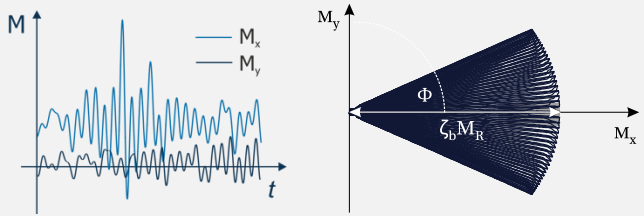
- Relatively low cost per test
- Captures key phenomenon
- Full control of geotechnical conditions
- Impacted by scale effects
- Unrepresentative geotechnical conditions

Regular, unidirectional tests at $1g$



Tests exploring stress-level

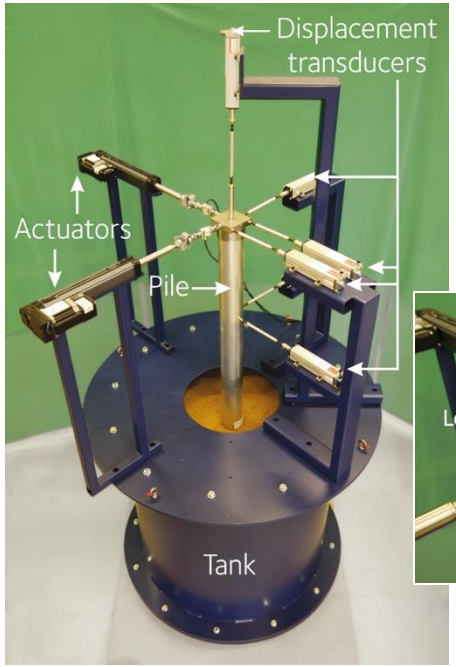
Multi-directional and multi-amplitude tests

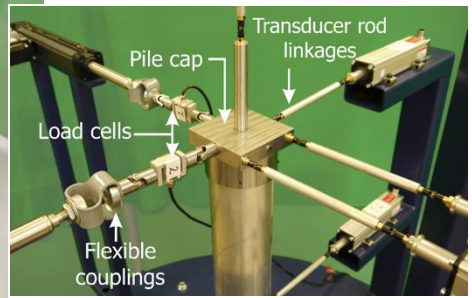


1g set-up

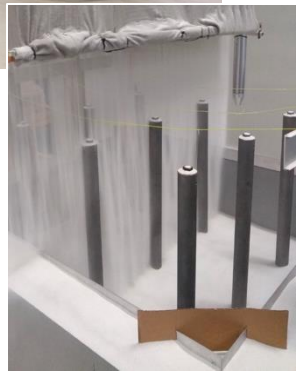
- 1g apparatus applies multidirectional, multi-amplitude cyclic loading
- Model pile diameter $D = 80$ mm
- Tests in dense dry (drained) sand ($R_D = 60\%$)

→ **Impact of load amplitude and directionality**





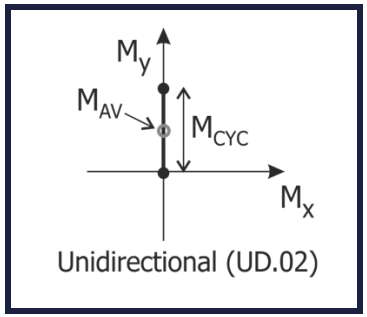
Centrifuge set-up

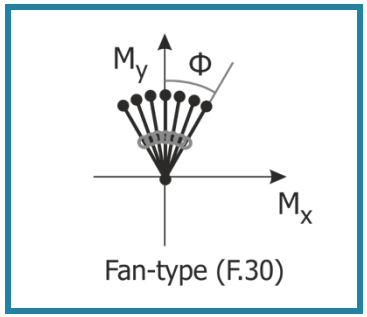


- Apparatus applies cyclic loading at 1g, 9g and 80g
- Modelling prototype pile diameters:
  - $D_p = 0.07$ m
  - $D_p = 0.64$ m
  - $D_p = 5.7$ m
- Tests in dense dry (drained) sand ($R_D = 87\%$)

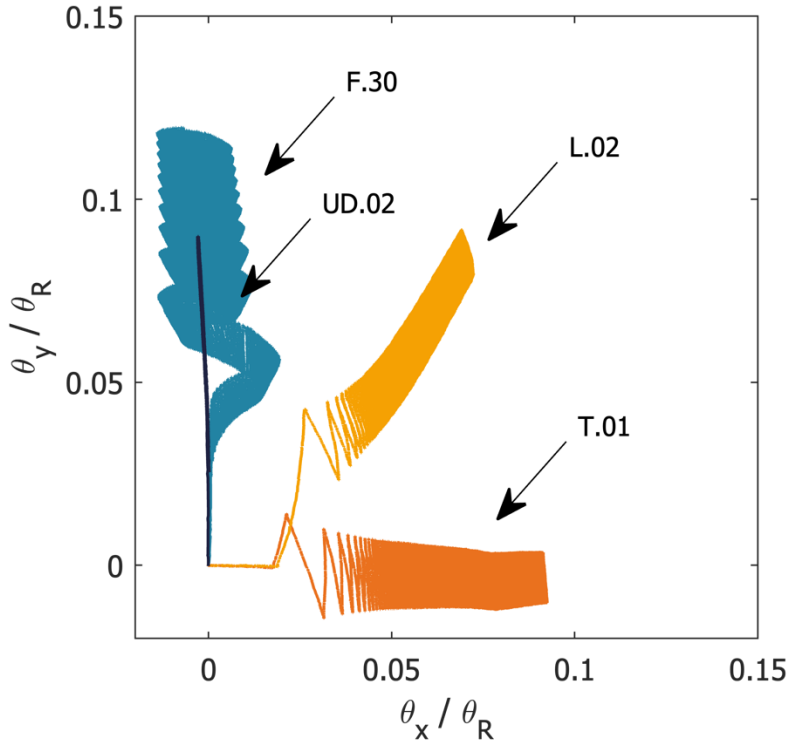
→ **Impact of stress-level**

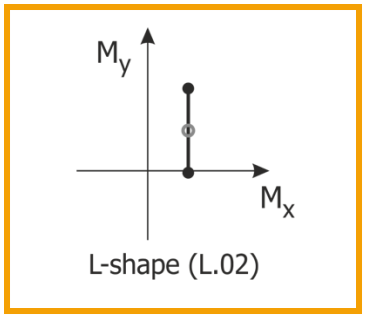
1g multidirectional test results

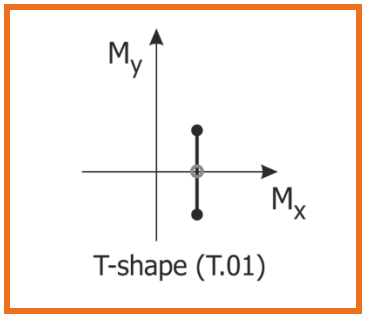




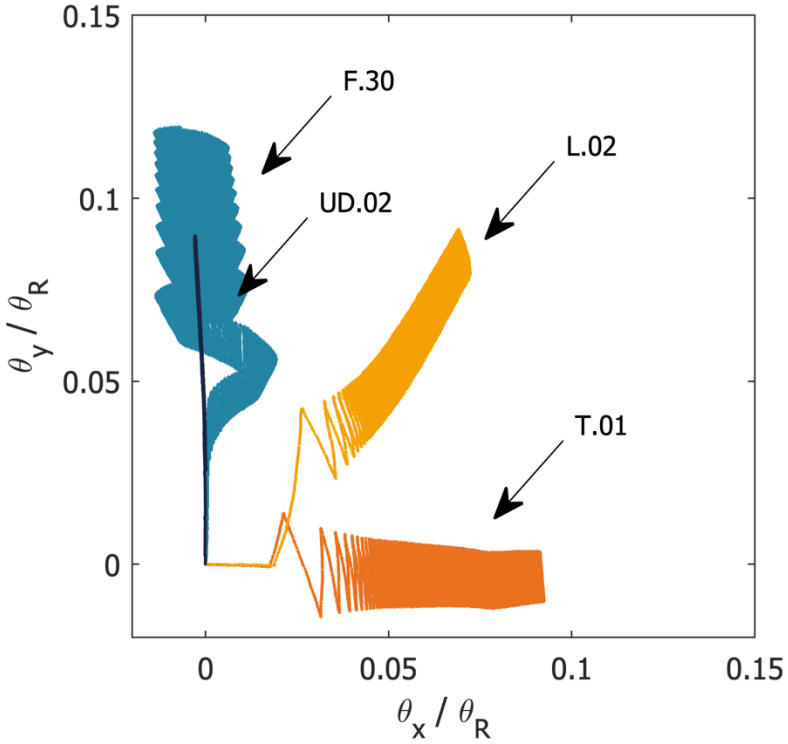
Normalised rotation response in "plan view"







1g multidirectional test results

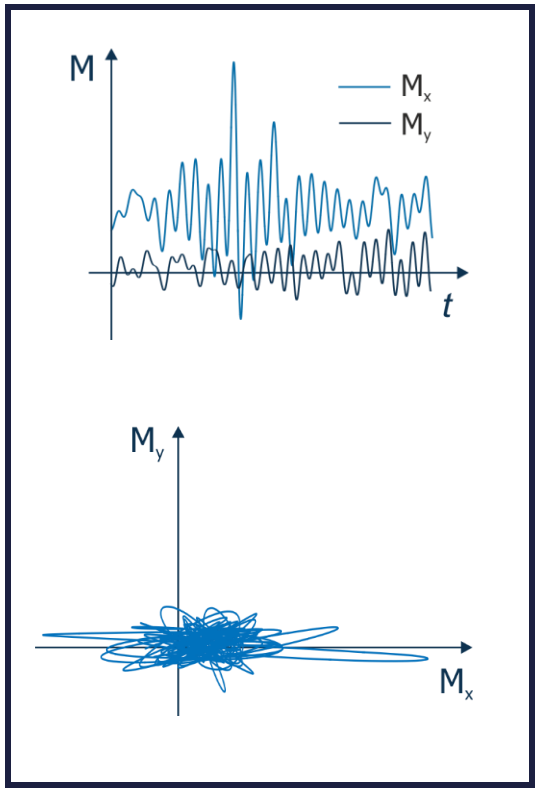


- Fan angle impacts the ratcheting response, with ratcheting power-law exponent α up to ~ 35% larger
- Ratcheting occurs in direction of mean load and is insensitive to cyclic load direction
- Misalignment of the cyclic and average load direction has minimal impact on ratcheting response

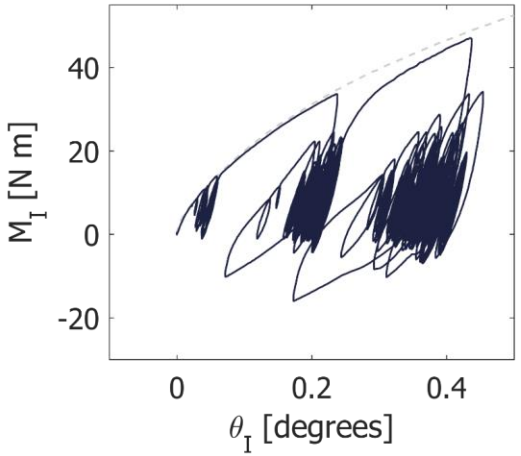
→ Systematic test results **inform development of models** capable of capturing response to multidirectional loading

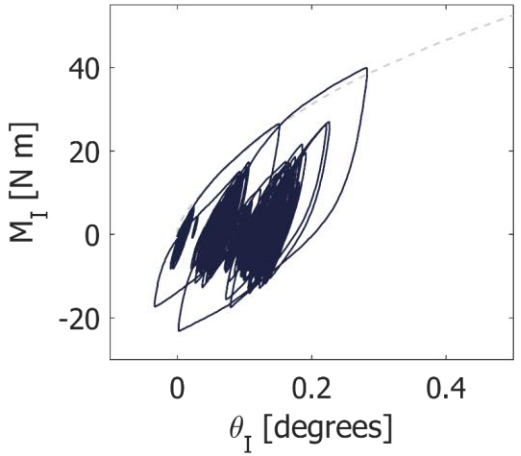
→ Results also show how **assumption of unidirectional loading can be non-conservative** in some cases

1g storm loading test results

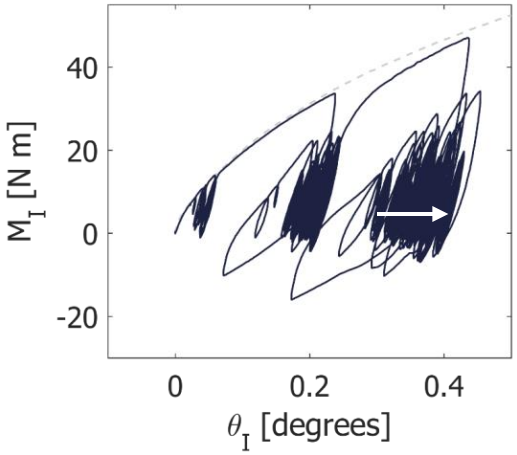


Example moment-rotation responses
(only principal loading direction shown)





1g storm loading test results



- Response is dominated by the large load events where response approaches (monotonic) backbone curve
- Ratcheting also occurs between large load events
- Response to storm loading consistent with observations from regular cyclic load tests

→ Response of monopile to realistic loading scenario is **valuable for model validation**

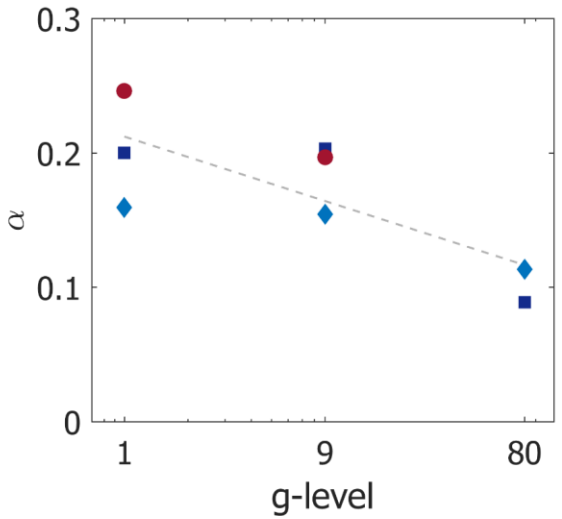
Centrifuge tests exploring stress-level effects

1g
$D_p = 0.07$ m

9g
$D_p = 0.65$ m

80g
$D_p = 5.77$ m

Power-law exponent α which defines rate of ratcheting, as a function of stress-level



- Qualitatively similar behaviour across stress-levels

→ Supports use of small-scale model tests to understand **key phenomenon**

- Reduction in ratcheting rate with increasing stress-level (and associated inhibition of particle rearrangement)

→ Necessary to **adjust any quantitative conclusions** from small-scale tests before applying at full-scale

→ At **full-scale** the ratcheting exponent α may be **50% of the value at 1g**

Summary

In general, small-scale 1g model tests are valuable for:

- Supporting development and validation of models for design, particularly as numerous, well-controlled tests are possible, and key behaviours can be isolated
- Informing development of large or full-scale test programs

Specifically, the results have shown:

- Ratcheting occurs in direction of mean load and is insensitive to cyclic load direction, but continuously-varying multidirectional loading can impact rate of ratcheting
- When applying realistic storm loading, response approaches backbone curve for large load events
- Rate of ratcheting decreases with increasing stress-level

Acknowledgements

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UNIVERSITY OF OXFORD

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