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Introducing the C1 Wedge Connection

Increasing loads on the connections of tubular towers that support wind turbines are making the traditional bolted L-flange more challenging to design, while the large mass of components and tools make installation challenging from a safety perspective. The C1 Wedge Connection is a symmetrical connection between tubular sections. The connection consists of a cylindrical lower flange and a fork-shaped upper flange that slides over the lower flange. Both flanges have radial elongated holes distributed along the perimeter allowing the C1 fasteners to pull the two flanges together. The fastener assembly of the C1 Wedge Connection uses a small, horizontally placed bolt to pull two wedges together. The wedges transform and magnify the horizontal bolt force into a larger preload between the flanges by pulling them together. The orientation of the bolt in the fastener prevents significant load fluctuations under external loading. As a result, unlike a bolted L-flange, the C1 Wedge Connection is less susceptible to preload loss, thereby eliminating the need for regular maintenance and inspection. The scalability of the C1 Wedge Connection makes it suitable for larger loads. These larger loads are expected with increasing size of wind turbines and when connections are used in more demanding locations such as hurricane and seismic conditions or where connections are subjected to high dynamic loads caused by extreme wave conditions or on floating foundations.

Keywords C1 Wedge Connection; flange connection; wind turbine; tower; monopile; transition piece

1 Background

In recent years the power output of offshore and onshore wind turbines has grown massively. Larger rotors combined with taller towers have significantly increased the loads on the connections that are used in offshore and onshore wind turbine towers and substructures. As a result, the traditional bolted L-flange connection which is typically used to connect towers to substructures and in between tower and substructure segments is subject to increasing loads and increasing load variations. Over the years this has driven up the bolt size in bolted L-flanges from the smaller diameters all the way up to M72 and even these sizes are not sufficient for some designs. The width and thickness of flanges have also had to scale up rapidly to match the increasing bolt size. As a result, the traditional bolted L-flange scales poorly with increasing loads. In addition to poor scalability, HSE (Health, Safety and Environment) issues are increasingly becoming a major concern. With M72 bolts already at the limit of allowable lifting weights, the tools required to torque and tension these bolts exceed the HSE allowable lifting limits, so additional lifting devices are needed inside the wind turbine generator (WTG) during installation and maintenance [1]. Traditional L-flanges require a high, well-defined, preload level in the connection to prevent excessive load fluctuations passing through the bolts [2]. Any gaps between the interfaces of the flanges therefore need to be closed by pulling the two flanges together [3]. The tubulars become stiffer as the load on the foundations increases, making gap closing more complicated. Typically, the bolts that are used in L-flanges require post-tensioning or torquing after a certain operating time and regular inspections are required to verify the proper preload level [4].

The issues associated with traditional flange connections have resulted in the development of the C1 Wedge Connection which started in 2017 with a MSc. Thesis [5]. The concept has gone through several iterative improvements. The company C1 Connections was established in 2019 with the aim of developing the connection and introducing it to the market. The technology is protected with several patents and pending patent applications. C1 Connections will design, manufacture and supply the C1 Wedge Connection fasteners (Fig. 3), the industry design and fabricate the flanges containing the fasteners.

2 The C1 Wedge Connection

The C1 Wedge Connection is suitable for tubular structures but it can also be used in other type of connections. Unlike an L-flange connection, the C1 Wedge Connection is a symmetrical connection which can be installed from one side of the connection.

It consists of three main steel components (Fig. 1): an upper flange with fork-shaped cross section, a cylindrical lower flange and a C1 fastener assembly. The upper and lower flange feature elongated holes perpendicular to the tower wall, in which the C1 fastener assembly is placed. The C1 fastener assembly connects the upper flange with the lower flange. It generates a large preload between the two flanges, making the C1 Wedge Connection a preloaded connection.

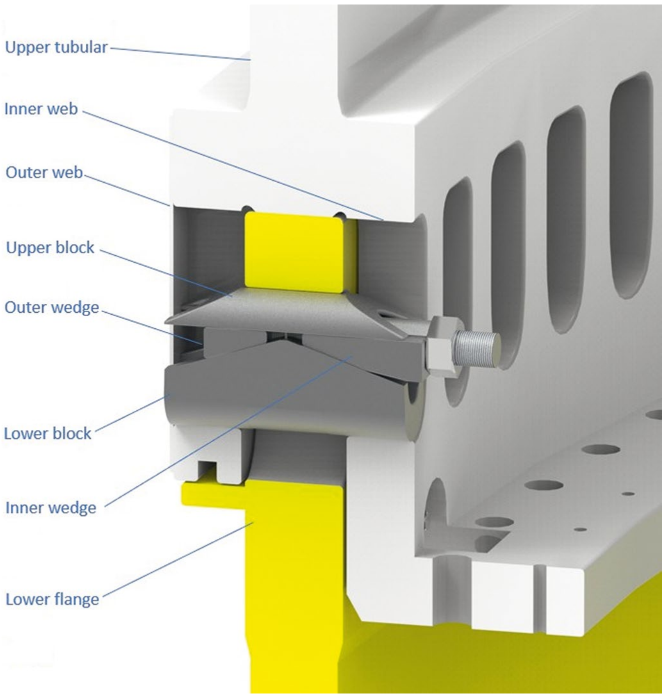

Fig. 1 Nomenclature of the main components of the C1 Wedge Connection

2.1 Components

2.1.1 Upper flange

The upper flange is a ring with a fork-shaped cross-section (Fig. 2). The vertical 'prongs' of the fork are referred to as webs, as they behave in a similar way to the web of an I-beam. Perpendicular holes are made in these webs to receive the C1 fastener. The bottom of the holes has the same radius as the C1 fastener. The holes are elongated such that the interface between the upper and lower flange is directly visible. The width of the holes is larger than the diameter of the C1 fastener. This ensures that the C1 fastener can tilt in case of a small tangential misalignment (see section 2.6).

The upper flange consists of three structural welded steel components: a solid connecting piece and an inner and outer web plate. These are welded and subsequently machined. The weld is affected by the preload; therefore, the fatigue resistance is drastically improved (see section 2.5.2). Optionally, a horizontal flange can be welded to the inner web. This flange has no structural function, but it is useful for attaching transport and lifting equipment.

The upper flange components are typically made of hot rolled or forged steel of grade S355 and above [6].

Another option is to forge a solid ring, and machine away a channel to create the fork-shaped cross section. The perpendicular holes are machined in a second operation.

2.1.2 Lower flange

The lower flange is a steel tubular with radial, elongated holes. The top of the holes has the same radius as the C1 fastener. The width of the holes is larger than the diameter of the C1 fastener. This ensures that the C1 fastener can tilt in case of a small tangential misalignment (see section 2.6).

The lower flange is typically made of structural steel of grade S355 and above [6].

2.1.3 C1 fastener

The C1 fastener consists of five main steel components: an upper and a lower block, an inner and outer wedge, and a bolt (or stud and nut) (Fig. 3). The lower block rests in the hole of the upper flange. After installation, the upper block is in contact with the hole of the lower flange. The wedges are placed in between the blocks, and are connected with the bolt. The outer wedge has a threaded hole, while the inner wedge has an oversized hole.

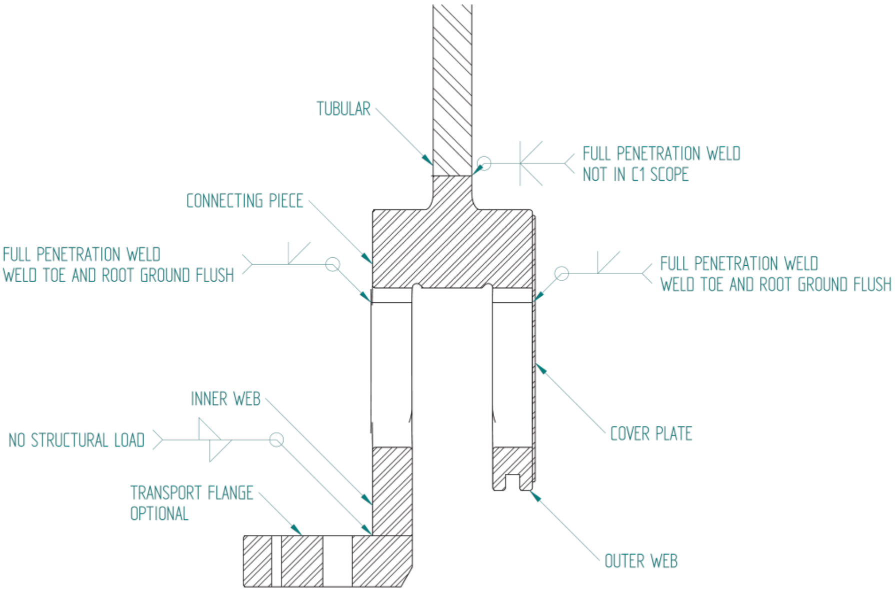

Fig. 2 Cross-section of welded upper flange

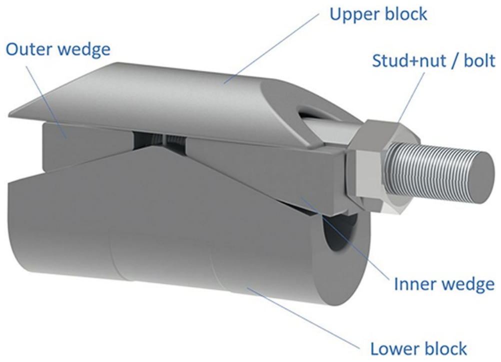

Fig. 3 C1 Wedge Connection fastener

When the bolt is torqued (or tensioned in case of a stud), the wedges are pulled together. The shallow slope of the wedges (typically < 20°) transforms the horizontal load from the bolt into a larger vertical preload.

The upper block is loaded mostly in compression, as it directly transfers the load from the wedges to the lower flange. Therefore the upper block is optimized to reduce its mass.

The lower block is loaded in bending because it spans between the webs of the upper flange, so its shape is optimized for bending resistance. The bottom of the lower block is modified to reduce stress concentrations in the webs.

The C1 fastener components are typically made of high-strength, quenched and tempered steels [7]. The heaviest component is the lower block. Note that the entire C1 fastener assembly can be pre-assembled on the upper flange (see 2.11), so no components need to be lifted on-site.

2.2 Preload equation

Preloading the bolt (or stud) pulls together the wedges in the C1 fastener. The head of the bolt exerts a horizontal load on the inner wedge, while the threads do the same on the outer wedge. Therefore, both wedges are loaded equally. The free body diagram (FBD, Fig. 4) is used to determine the resulting vertical preload. Each wedge is assumed to generate half of the vertical preload F_{pre}. Consider the horizontal load equilibrium of the inner wedge:

$$\sum F_{\text{hor}} = 0$$

$$F_{\text{bolt}} = F_{\text{hor}} + F_{\text{friction},1} + F_{\text{friction},2,\text{hor}}$$

$$F_{\text{bolt}} = F_{\text{hor}} + F_{\text{friction},1} + \frac{F_{\text{friction},2}}{\sin(\beta)}$$

$$F_{\text{bolt}} = \frac{F_{\text{pre}}}{2} * \tan(\beta) + \frac{F_{\text{pre}}}{2} * \mu + \frac{\frac{F_{\text{pre}}}{2} * \sin(\beta) * \mu}{\sin(\beta)}$$

$$F_{\text{bolt}} = F_{\text{pre}} * \left(\frac{1}{2}\tan(\beta) + \mu\right) \tag{1}$$

With the typical slope and friction coefficient $\beta = 18°$, $\mu = 0.05$, Eq. (1) results in a magnification of the bolt load with a factor of 4.71. Therefore, to generate a similar preload as a bolted L-flange connection, a much smaller bolt size can be used.

2.3 Load paths

The load transfer of the C1 Wedge Connection is typically analyzed considering the segment load. The external overturning moment is translated into tensile and compressive loads per segment.

2.3.1 Tensile load – fully preloaded

The preloaded C1 Wedge Connection has two load paths for tensile loads. The primary load path is by reduction of the preload between the upper and lower flange. The secondary load path is by transferring the load via the webs of the upper flange, through the C1 fastener and onto the lower flange. The ratio between these two load paths is equal to the stiffness ratio η, defined as (Eq. (2)):

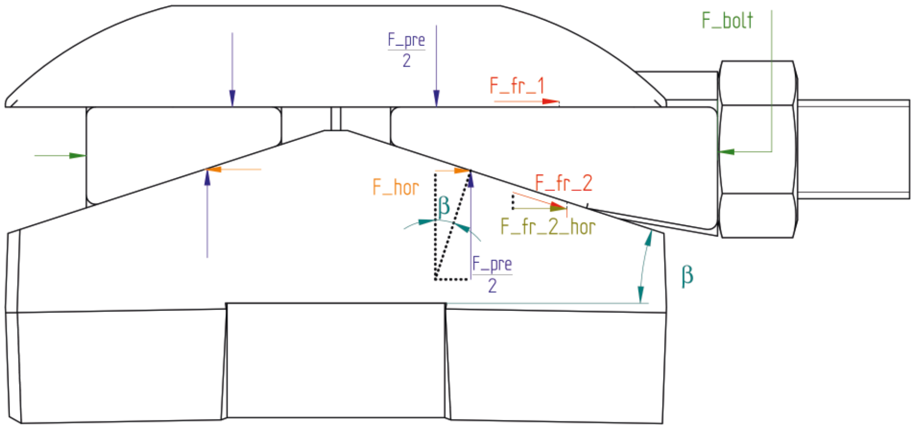

Fig. 4 Simplified free body diagram of the C1 fastener

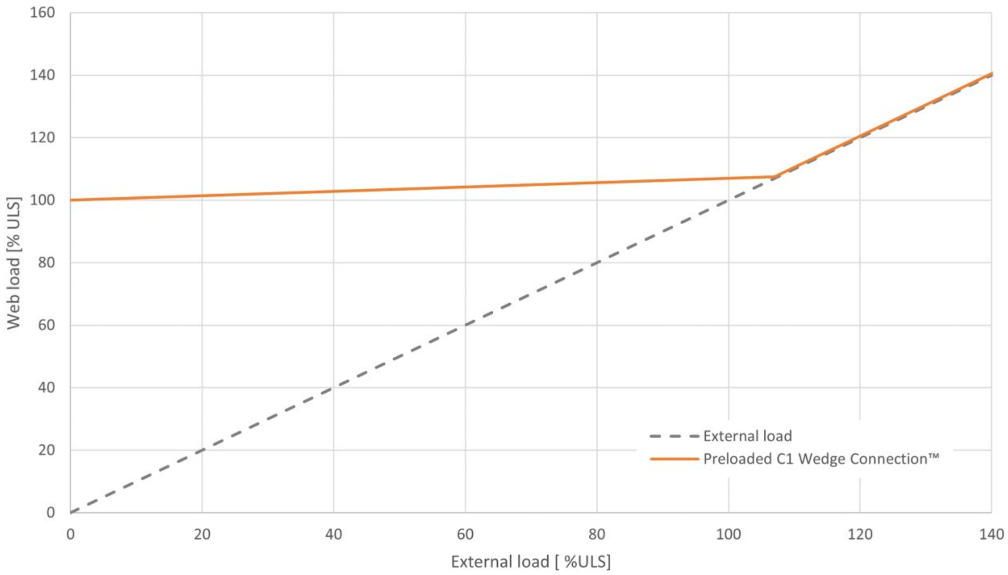

Fig. 5 Web load vs external load for preloaded C1 Wedge Connection; axes are normalized to ULS load

$$\eta = \frac{k_{\text{secondary}}}{k_{\text{primary}}} = \frac{\Delta F_{\text{web}}}{\Delta F_{\text{external}}} \tag{2}$$

For typical designs, $0.05 \le \eta \le 0.1$.

If the external load exceeds the preload * $(1 + \eta)$, the full load is transferred through the secondary load path. This relation is plotted in Fig. 5.

2.3.2 Tensile load – without preload

If the C1 Wedge Connection is not preloaded, the tensile load is transferred fully through the ‘secondary load path’ as described in 2.3.1.

2.3.3 Compressive load

Compressive loads are always transferred directly from the upper to the lower flange. The holes in the flanges are oversized such that the C1 fastener cannot transfer any compressive loads (Fig. 1).

2.3.4 Shear and torsional loads

Shear and torsional loads are always transferred from the upper to the lower flange through friction in the interface. Friction is generated by three different normal loads: the normal load from the structure mass, the compressive part of the overturning moment and the preload generated by the C1 fastener.

2.4 ULS resistance

The Ultimate Limit State (ULS) resistance of the C1 Wedge Connection is governed by the wall thickness of the lower flange and the webs of the upper flange. Two factors are considered: the net stress between the holes and the contact pressure in the holes. Typically, the maximum tensile load per segment of the connection is used for design purposes:

$$Q_{\text{d}} = \frac{4M_{\text{d}}}{\pi D^2} \left[\frac{\text{MN}}{\text{m}}\right] \tag{3}$$

$$F_{\text{seg,d}} = Q_{\text{d}} * l_{\text{seg}} = Q_{\text{d}} * \frac{\pi D}{N_{\text{segments}}} = \frac{4M_{\text{d}}}{D * N_{\text{segments}}} [\text{MN}]$$

where:

Q_{d} = design line load $\left[\frac{MN}{m}\right]$

l_{seg} = segment length [m]
M_{d} = design overturning moment [MNm]
D = structure diameter [m]
N_{seg} = number of segments [–]

Eq. (3) for line-load Q is derived in section 5.

The net stress design criterion is as follows, based on [8]:

$$\sigma_{\text{net,d}} \le \frac{f_{\text{y}}}{\gamma_{\text{M,1}}}$$

With typically $\gamma_{\text{M,1}} = 1.1$, and (Eq. (4)):

$$\sigma_{\text{net,d}} = \frac{F_{\text{seg,d}}}{t * \left(l_{\text{seg}} - D_{\text{hole}}\right)} \tag{4}$$

The contact pressure design criterion is as follows [8]:

$$p_{\text{contact}} \le \frac{f_{\text{y}}}{\gamma_{\text{M,2}}}$$

with typically $\gamma_{\text{M,2}} = 1.25$, and (Eq. (5)):

$$p_{\text{contact}} = \frac{F_{\text{seg,d}}}{t*\left(D_{\text{fastener}}\right)} \tag{5}$$

2.4.1 Optimized number of C1 fasteners

For an optimal design, the utilization on both net stress and contact pressure is equal (Eq. (6)):

$$\frac{\sigma_{\text{net,d}}}{\dfrac{f_y}{\gamma_{M,1}}} = \frac{p_{\text{contact}}}{\dfrac{f_y}{\gamma_{M,2}}} \tag{6}$$

Therefore, $\dfrac{\sigma_{\text{net,d}}}{p_{\text{contact}}} = \dfrac{\gamma_{M,2}}{\gamma_{M,1}} = \dfrac{1.25}{1.1} = 1.14$

To account for manufacturing and installation tolerances (see section 2.6), typically $D_{\text{hole}} = 1.15 * D_{\text{fastener}}$. This can be used to determine the ratio between the segment's length and the C1 fastener diameter. Taking this into account in the equation for net stress (Eq. (4)):

$$\sigma_{\text{net,d}} = \frac{F_{\text{seg,d}}}{t*\left(l_{\text{seg}} - 1.15*D_{\text{fastener}}\right)}$$

The equation for equal utilization (Eq. (6)) is now:

$$\frac{\left(\dfrac{F_{\text{seg,d}}}{t*\left(l_{\text{seg}} - 1.15*D_{\text{fastener}}\right)}\right)}{\left(\dfrac{F_{\text{seg,d}}}{t*D_{\text{fastener}}}\right)} = 1.14$$

This simplifies to:

$$\frac{D_{\text{fastener}}}{l_{\text{seg}} - 1.15\,D_{\text{fastener}}} = 1.14$$

$$l_{\text{seg}} = 2.02*D_{\text{fastener}}$$

With a typical C1 Wedge Connection fastener diameter of 100 mm, this implies a segment length of 202 mm, or approximately 5 C1 fasteners per m circumference. It is recommended to round the number of C1 fasteners to a multiple of 6 to easily incorporate features for alignment and quick connection.

If pile driving is considered on the lower flange, as in a monopile-to-transition-piece connection, a larger net cross-section may be required. This will reduce the number of C1 Wedge Connection fasteners.

2.4.2 Preload and bolt size

The relation between bolt preload and vertical preload was derived in section 2.2. C1 Connections has extensively tested (section 3.5) the relation between bolt load and vertical preload to verify this relation and determine the friction coefficient. With a coated and lubricated C1 fastener set, a design friction coefficient (upper bound, 5 % exceedance value) of approx. 0.05 was obtained.

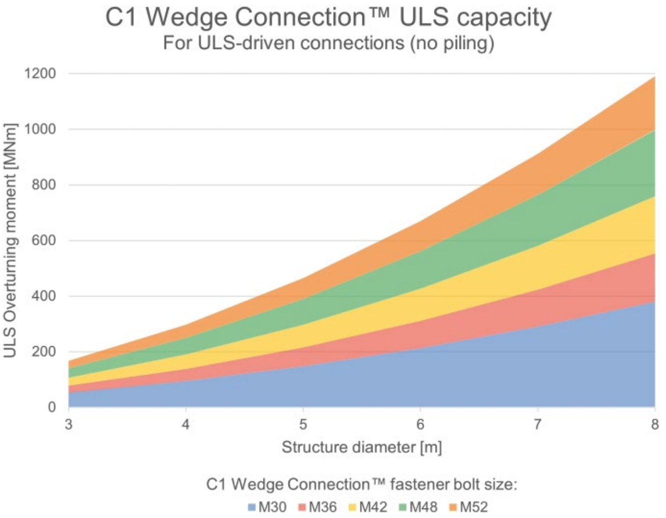

Fig. 6 Overturning moment vs diameter for selected bolt sizes

With a typical C1 fastener design (M36, grade 10.9 bolt), a vertical preload of ~2400 kN can be obtained. The corresponding ULS overturning moment is plotted for different diameters in Fig. 6.

2.5 Fatigue resistance

2.5.1 Lower flange

The most critical component in the Fatigue Limit State (FLS) is typically the hole in the lower flange. The lower part of the hole is not affected by the preload and so experiences the full load range. However, as this is a detail machined from base material, it has a very high detail category. The shape of the hole is optimized to minimize the stress concentration. A design S-N curve based on scaled segment fatigue tests can be used (see section 3.4) for detailed design purposes. This fatigue resistance of the detail (97.7 % probability of survival, 75 % confidence, in accordance with [9]) is given in Eq. (7).

$$\log_{10}\left(N\right) = 13{,}457 - 4*\log_{10}\left(\Delta\sigma_{\text{nom}}\right) \tag{7}$$

where $\Delta\sigma_{\text{nom}} = \dfrac{\Delta F_{\text{seg}}}{l_{\text{seg}} * t_{\text{lower}}}$

A more detailed FLS analysis should be based on the FE analysis of a specific design. The critical fatigue damage can be assessed by applying the detail category of the base material (DNV-B1 [9] or DC160 [10]) to the largest stress range found in the lower flange. Typically, the largest stress range is found at the smallest cross-section of the hole (Fig. 7).

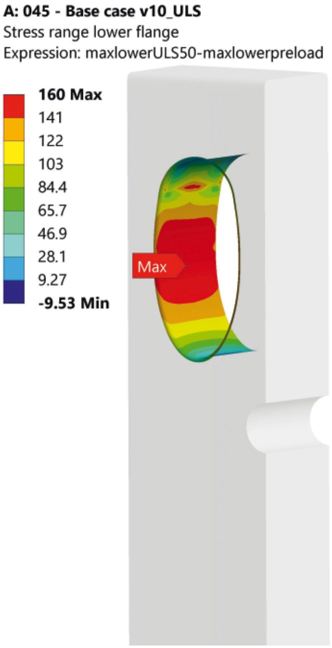

Fig. 7 Maximum principal stress range in lower flange between preload and 50 % ULS load – for a reference case

2.5.2 Welded upper flange

If a welded upper flange is used, the fatigue damage in the welds can be assessed by using the stiffness ratio η (section 2.3.1) to determine the load going through the welds. With this reduced load range the stress range in the welds can be calculated. Fatigue damage can be determined based on standard detail categories, typically DNV category C ([9], equivalent to DC 125 [10]) for full-penetration butt welds with both the weld toe and root ground/machined flush. With the typical stiffness ratio (section 2.3.1) of less than 10 %, the load range in the webs is reduced such that the stress range in the weld is below the endurance limit as defined in DNV-RP-C203, therefore resulting in infinite fatigue life.

2.5.3 C1 Wedge Connection fastener

The load range through the C1 Wedge Connection fastener is reduced by the preload, in the same way as the upper flange webs. Because the C1 fastener is made entirely of forged and machined high-strength steel base material, it has a high fatigue resistance. With the typical stiffness ratio (section 2.3.1) of less than 10 %, the load range in the C1 fastener is reduced such that the stress range in the C1 fastener components is below the endurance limit as for high-strength steels [11], therefore resulting in infinite fatigue life.

2.5.4 Bolt

As the bolt is perpendicular to the load, it experiences a reduced load range. Consider again the horizontal load equilibrium of the inner wedge, as in the free body diagram (FBD) in Fig. 8. The horizontal force equilibrium of the inner wedge when loaded by an external load is given by:

$$\Sigma F_{\text{hor}} = 0$$

$$F_{\text{hor}} = 2 * F_{\text{fr}} + F_{\text{bolt}}$$

$$\frac{\Delta F_{\text{fastener}}}{2} * \tan(\beta) = 2 * \frac{\Delta F_{\text{fastener}}}{2} * \mu + F_{\text{bolt}}$$

$$\Delta F_{\text{bolt}} = \Delta F_{\text{fastener}} \left(\frac{\tan(\beta)}{2} - \mu \right)$$

With the C1 fastener slope β = 18°, and μ = 0.05, $\Delta F_{\text{bolt}} = 0.112 \Delta F_{\text{fastener}}$.

Considering that $\Delta F_{\text{fastener}} = \eta \Delta F_{\text{ext}}$ while $F_{\text{ext,max}} < F_{\text{open}}$, with typical $\eta = 0.075$, the bolt force range is found as:

$$\Delta F_{\text{bolt}} = \eta * \left(\frac{\tan(\beta)}{2} - \mu \right) \Delta F_{\text{ext}} = 0.0084 \Delta F_{\text{ext}}$$

The force range in the bolt is so low that it results in stresses below the endurance limit, resulting in infinite fatigue life in the bolt.

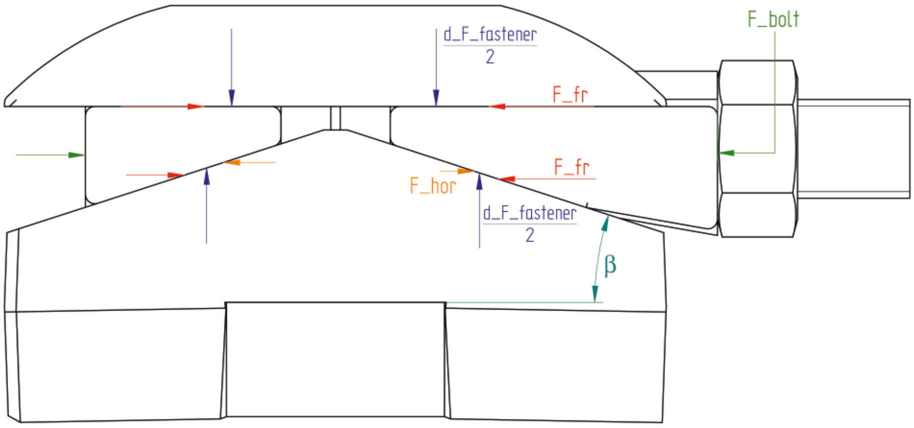

Fig. 8 Simplified free body diagram of the C1 fastener under external load

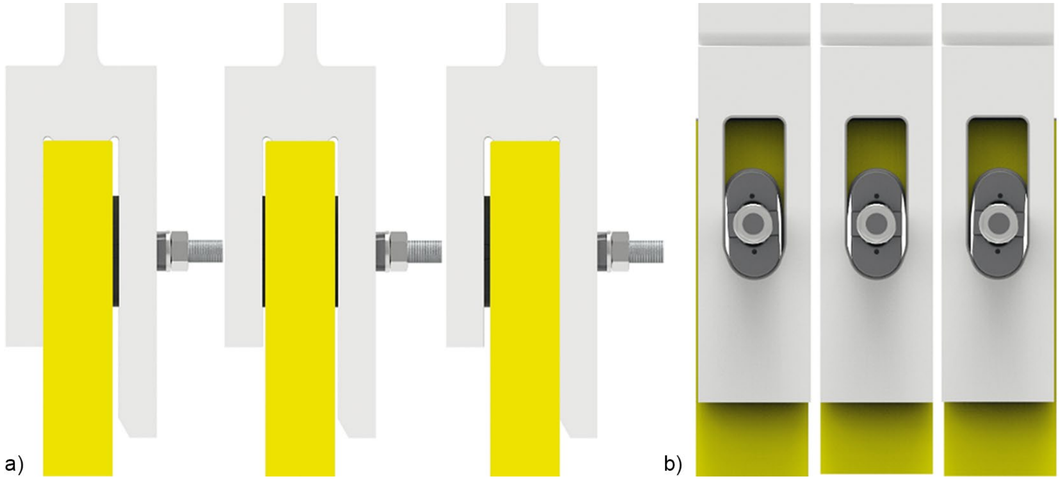

Fig. 9 a) Radial misalignment, b) tangential misalignment

2.5.5 Minimum preload level

If the preload level is lower than the external load per segment, the full external load is transferred through the upper flange and C1 fastener. In this case the fatigue damage found in the upper flange web welds increases. Nevertheless, for a typical load spectrum, the upper flange welds can be designed such that even without any preload, the fatigue damage in the welds is acceptable. The same goes for the C1 fastener, as it was shown using the FBD in Fig. 8 that the bolt load range is approx. 10 % of the external load range. In that case the minimum preload level is not determined by fatigue resistance, but rather by the friction required to transfer shear and torsion loads. As the normal load and the compressive part of the overturning moment also help to generate friction in the interface between the flanges, the required preload is (close to) zero.

2.6 Tolerances

The design of the C1 Wedge Connection inherently accounts for several manufacturing and installation tolerances (Fig. 9). The upper flange can be misaligned with respect to the lower flange in the radial direction, as the space between the inner and outer web is larger than the thickness of the lower flange. At the same time, the C1 fastener can tilt in the holes in the upper and lower flange (tangential direction).

A topic of specific interest is flatness tolerance ('waviness'). The C1 Wedge Connection is less susceptible to waviness for three reasons:

- The source of waviness (heat input from welding) is reduced:
  - The lower flange is welded quite far away from the interface
  - The upper flange has high bending stiffness in the vertical direction
- Any gaps due to waviness can be largely eliminated during installation because:
  - the lower flange has relatively low stiffness
  - the C1 fasteners generate a high preload
  - if required, shimming is easy as the interface can be directly measured/shimmed through the elongated holes in the upper flange (Fig. 1).
- The connection is not very sensitive to the exact amount of remaining preload after closing any gaps because:
  - the fatigue resistance is very high
  - the fatigue critical component is typically the lower flange, which is not significantly affected by the preload level.

C1 Connections has performed extensive research into the response of the C1 Wedge Connection to flatness imperfections and is preparing a publication about this topic. An initial study for a previous geometry of the connection was published in a MSc. Thesis [12].

2.7 Loss of bolt preload

A significant fraction of the bolt preload can be lost before the connection itself sees a reduction in preload. This is due to the friction generated in the C1 fastener. Consider the FBD of Fig. 4, with the inner wedge at the point of sliding. In that case:

$$\Sigma F_{\text{hor}} = 0$$

$$F_{\text{bolt,critical}} + F_{\text{friction}} = F_{\text{hor}}$$

$$F_{\text{bolt,c}} = F_{\text{hor}} - F_{\text{fr}}$$

$$F_{\text{bolt,c}} = \frac{1}{2} F_{\text{pre}} * \tan(\beta) - F_{\text{pre}} * \mu$$

$$F_{\text{bolt,c}} = F_{\text{pre}} \left(\frac{1}{2} \tan(\beta) - \mu \right)$$

Recall Eq. (1):

$$F_{\text{bolt,preload}} = F_{\text{pre}} * \left(\frac{1}{2}\tan(\beta) + \mu\right)$$

$$\frac{F_{\text{bolt,c}}}{F_{\text{bolt,preload}}} = \frac{\frac{1}{2}\tan(\beta) - \mu}{\frac{1}{2}\tan(\beta) + \mu} = 0.53$$

With the typical values ($\beta = 18°$, $\mu = 0.05$), the critical bolt load is approx. 53 % of the bolt preload. In other words, nearly half of the bolt preload can be lost before any vertical preload reduction is found.

This was also proven in experiments, see section 3.5.

2.8 Manufacturing

Manufacturing the main components of the C1 Wedge Connection is straightforward, especially if the welded upper flange is chosen. The tubulars are machined on large machining centers, which are available worldwide. So far three full-scale connections have been manufactured by C1 Connections and partners, with diameters ranging from 3.5 to 7 m.

2.9 Sealing and corrosion protection

The connection is sealed from water ingress. Each individual component is protected by a coating system adequate for its environment. The large holes in the upper flange are covered by (welded) cover plates. The space between the upper and lower flange is covered by a compressible seal. This seal is pressed against a dedicated ring welded to the lower flange (Fig. 10).

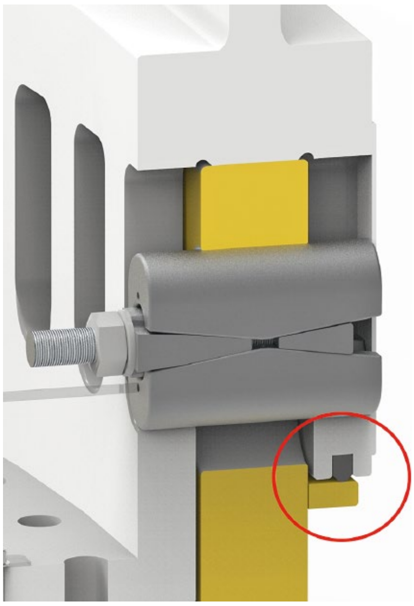

Fig. 10 External seal in the outer web

2.10 Pile installation

If the C1 Wedge Connection is used as a connection between a monopile and a transition piece, the lower flange of the connection will be the top part of the monopile. In that case, the pile installation must be considered.

2.10.1 Impact driving

For applications where the lower flange is directly integrated in a foundation pile, the piling load case should be considered. Typically, the increased wall thickness and material quality of the lower flange reduce the nominal stresses from piling. The geometry of the top of the lower flange can be optimized to reduce local stresses. An stress concentration factor (SCF) of 3.75 was found in a detailed piling investigation. This typically results in some local plastic deformation, but it has been demonstrated this is not progressive and therefore acceptable.

It is recommended to perform a detailed piling study if piling on the lower flange of the C1 Wedge Connection is foreseen (Fig. 11).

2.10.2 Vibratory pile installation

The lower flange of the C1 Wedge Connection can easily be gripped by vibratory installation tools, as there is no large protruding flange.

2.10.3 Drilling

The lower flange of the C1 Wedge Connection facilitates drilling tools, as there is no large flange protruding in-

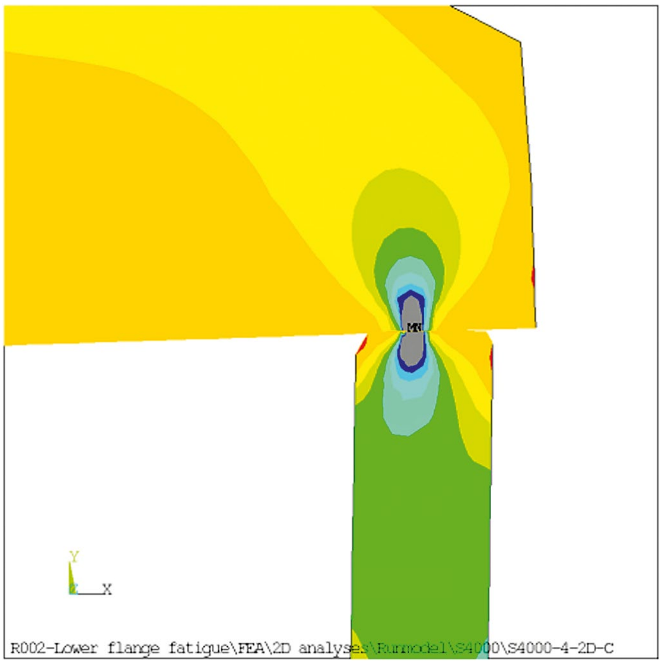

Fig. 11 Example stress plot lower flange in piling

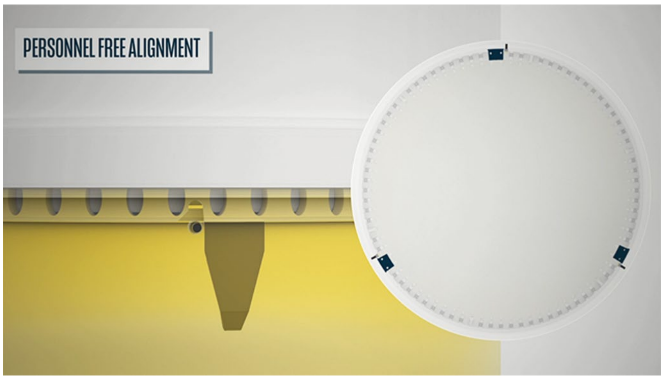

Fig. 12 View of alignment seeker and pin, just before landing

wards. This minimizes the distance an underreamer needs to span.

2.11 Installation of the connection

Installation of the C1 Wedge Connection is very straightforward and safe. It is divided into four stages: alignment, quick connection, rundown and final preloading. The C1 fastener assemblies can be pre-assembled in the upper flange (Fig. 14). Therefore, no components need to be lifted manually on-site.

2.11.1 Alignment

The lower flange is fitted with alignment pins which protrude perpendicular to the wall of the tubular. The bottom of the inner web has matching cut-outs. Additionally, downwards pointing seekers are attached to the upper flange. When the upper flange is lowered, the seekers provide a coarse alignment (Fig. 12). The alignment pins ensure a close alignment of the holes. Thanks to this system, no personnel needs to be present at the connection level during lifting.

2.11.2 Quick connection

Once the upper flange has landed on the lower flange, the quick connection system is activated. This consists of a set of radially moving pins which are displaced outwards by an actuation system (automatic or remote-operated) (Fig. 13). The pins fit into the holes in the lower flange. This ensures a quick connection which can resist significant overturning moment between the lower and upper tubular. This quick connection can be made in seconds, allowing a fast release of the main crane hook. The main installation vessel can now sail away.

2.11.3 Rundown

The C1 Wedge Connection fasteners are pre-assembled on the upper flange (Fig. 14). The rundown process is done in two steps: sliding in the C1 fasteners and running down the bolt/nut. No heavy components have to be lifted manually. Rundown can be done with lightweight, battery-operated handheld tools. After rundown of the bolt, the full ULS capacity of the connection is reached.

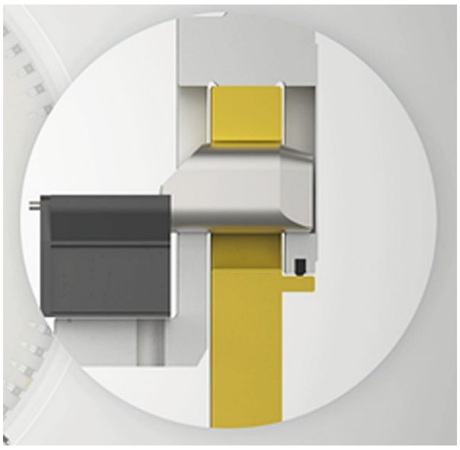

Fig. 13 Concept design of quick connection system

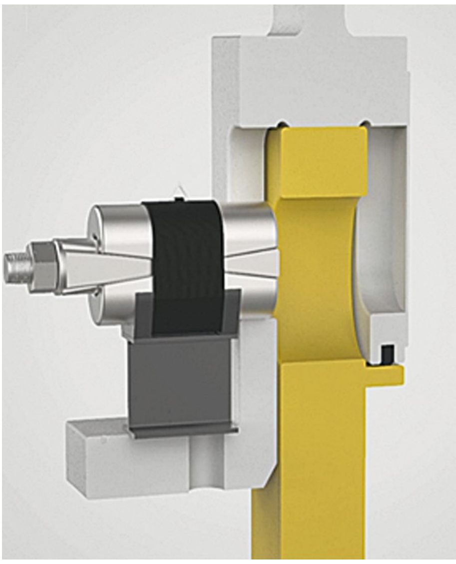

Fig. 14 Pre-assembled C1 fastener

2.11.4 Final preloading

Final preloading of the C1 Wedge Connection is done by preloading the bolt/stud. Both torquing and tensioning methods can be used for preloading of the bolt. Tensioning is more accurate. The connection in general is not sensitive to the exact preload level. Due to the shallow slope of the wedges, a relatively long stroke is required to reach full preload. This must be taken into account when selecting the preloading method.

2.12 Inspection and maintenance

As discussed in sections 2.5 and 2.7, the connection is not sensitive to the exact preload level in the bolt. Therefore, no inspection and/or maintenance is necessary.

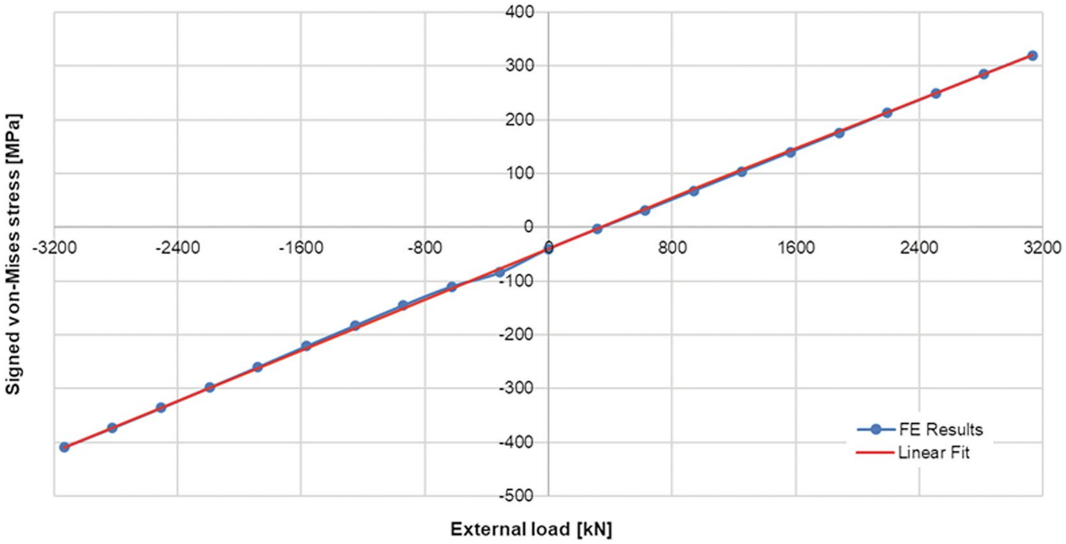

Fig. 15 Typical stress transfer function for the node with largest stress range in the lower flange

3 Physical evidence

C1 Connections has performed a number of physical tests, and extensive analytical and numerical analyses to prove the concept of the C1 Wedge Connection.

3.1 Analytical design

The initial design is based on the analytical equations discussed in section 2.4. Based on C1 Connections' experience, nearly all connection designs are governed by ULS loading. Fatigue verification is based on DEL loads or preferably on full Markov matrix load spectra. C1 Connections is preparing a case study publication for a reference design.

3.2 Numerical analysis

Due to the 3D nature of the connection, the relatively large number of contacts and high local stresses, it is recommended to perform dedicated finite element analyses when designing a C1 Wedge Connection. An example analysis will be part of a future publication by the authors.

Initial finite element analyses can be based on a single segment, loaded with the ULS tensile and compressive segment load as derived in section 2.4. For fatigue analysis, the node where the largest stress range is found is selected and the transfer function between external load and signed von Mises stress is extracted for that node. This is typically a linear relation (Fig. 15).

3.3 Full-scale mock-up

Fig. 16 Photo of the ∅4.5 m mock-up

In 2020, C1 Connections built the first full-scale connection in Delft, The Netherlands. An upper and lower flange were produced at ∅4.5 m. The upper flange was assembled and the installation process followed. This mock-up was also used to perform verification tests of the preloading and closing of waviness. A video of this test is available online [13].

A second, ∅3.5 m mock-up has been fabricated. This mock-up includes the welded upper flange concept (Fig. 17).

3.4 Fatigue tests

Together with Delft University of Technology, approx. 3000 hours of scaled fatigue tests were performed (Fig. 18). These tests were executed at load ranges corresponding from 40 % to 120 % of design ULS load. The main result of these tests is the verification of the SN-curve (Eq. (7)) to be used in the design of the connection. In tests, the lower flange was consistently found to be the critical component. The results of these tests and tests obtained on the latest generation of the wedge connection will be discussed in a future publication.

Fig. 17 ∅3.5 m mock-up during transportation

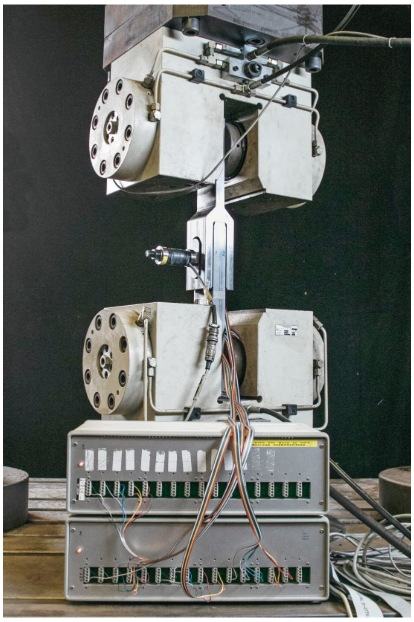

Fig. 18 Scaled fatigue test setup at TU Delft

3.5 C1 fastener tests

C1 Connections has developed a custom test bench (Fig. 19) to test the relation between bolt load and vertical preload of the C1 Wedge Connection fastener. These tests are used to determine the friction, and correspondingly the amount of preload to be applied to the bolt. This test bench can be used to test C1 fasteners and/or lubricants for specific projects.

The measurements from these tests (Fig. 20) also validate the allowable preload loss in the bolt, as discussed in section 2.7. After tightening the bolt (linear upward part of the measured data in Fig. 20), the bolt load is reduced by untightening the bolt. For the initial ~ 45 % reduction of bolt load, the measured vertical preload remains constant (horizontal part of Fig. 20). This validates the critical bolt load, derived as 53 % of the applied bolt as derived in section 2.7.

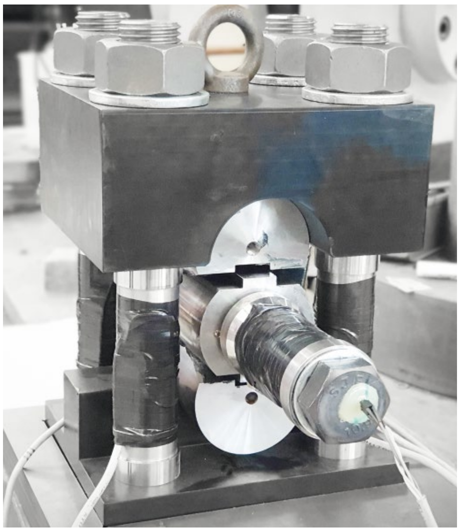

Fig. 19 Full-scale C1 fastener preload testing

3.6 Imperfection analyses

The impact on ULS and FLS resistance of several different imperfections has been studied with dedicated FE analyses:

- Radial misalignment
- Tangential misalignment
- Combination of radial and tangential misalignment
- Lower preload levels
- Flatness imperfections (waviness)

The results of these investigations will be published in a future publication.

4 Conclusion

The C1 Wedge Connection is a new connection for tubular structures. It consists of three main steel components: the cylindrical lower flange, the fork-shaped upper flange and the C1 Wedge Connection fastener assembly. The upper flange is placed over the lower flange, while the C1 fastener assembly is inserted through radial elongated holes around the circumference of both flanges. This forms a symmetrical connection around the neutral axis of the tubular shell. The result is an even load distribution over the components of the connection.

The C1 fastener assembly transforms and magnifies a relatively small, horizontal bolt load into a larger, vertical preload. The vertical preload is transferred to the flanges. This makes the connection behave like a preloaded connection, with two distinct load paths for external tensile loads. This is similar to a bolted L-flange.

Typically, the connection design is governed by ULS loads. The dimensions of the connection can easily be determined based on analytical relations. The fatigue resistance of the connection is very high, as the fatigue critical detail is machined in base material (the hole in the

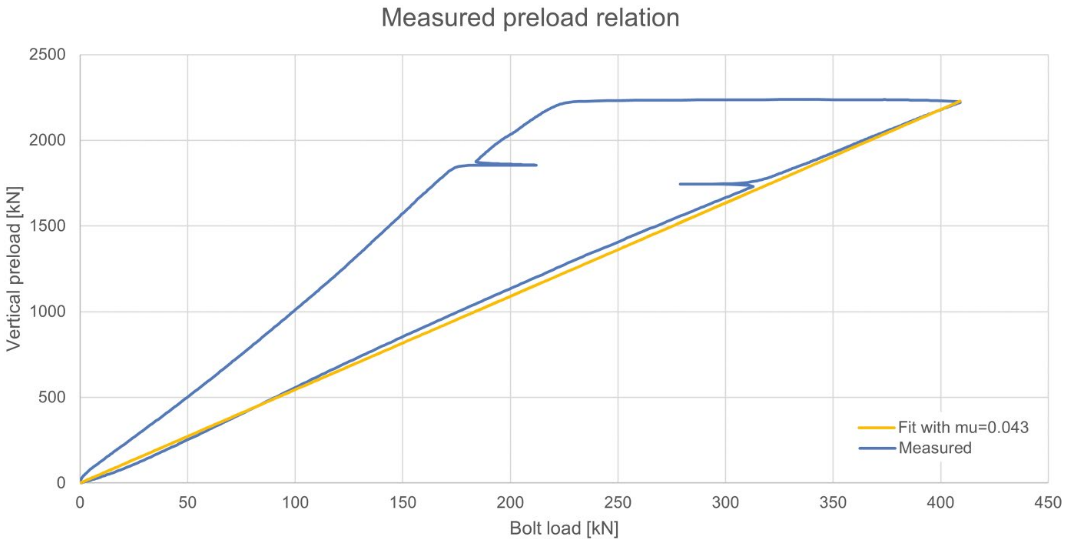

Fig. 20 Vertical load vs. bolt load, as measured using the fastener test setup; with fit line to determine friction coefficient

lower flange). Correspondingly, the connection can resist fatigue loads even with a severely reduced preload level.

Both ultimate resistance and fatigue resistance have been verified with elaborate experiments and extensive modelling with FE software.

The connection can be manufactured using the tower, monopile and flange suppliers' existing facilities. The installation of the connection is fast and safe. No personnel is present during lifting. Because of the superior fatigue resistance of the connection, it requires no inspection and maintenance.

Appendix A: derivation of line load *Q*

The line load Q is used as a diameter-neutral metric to determine and compare the loads on a connection in a tubular structure. It is derived from the overturning moment and diameter of the structure. The tubular cross-section is considered as thin-walled. Consider the equation for bending stress:

$$\sigma_\mathrm{b} = \frac{M * x}{I_\mathrm{x}}$$

where:

M = overturning moment [MNm]
x = coordinate of the considered fiber [m]
I_x = area moment of inertia [m^4]

For a thin-walled, cylindrical cross-section of diameter D and wall thickness t:

$$x_\mathrm{max} = R = \frac{D}{2}$$

$$I_\mathrm{x} = \pi R^3 t$$

correspondingly:

$$\sigma_\mathrm{b,max} = M * \left(\frac{R}{\pi R^3 t}\right)$$

$$\sigma_\mathrm{b,max} = M * \left(\frac{1}{\pi R^2 t}\right)$$

The line load is found by assuming the maximum bending stress over a segment with unit length:

$$Q = \sigma_\mathrm{b,max} * A_\mathrm{unit} = \sigma_\mathrm{b,max} * t * 1 = \sigma_\mathrm{b,max} t$$

combining:

$$Q = \sigma_\mathrm{b,max} t = \frac{M}{\pi R^2 t} t = \frac{M}{\pi R^2}$$

and substituting $R = D/2$:

$$Q = \frac{M}{\pi \left(\frac{D}{2}\right)^2} = \frac{4M}{\pi D^2}$$

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