The design of a suspended concrete transport pipeline system

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Synopsis

In order to deliver a quality shotcrete and concrete product underground for the extensions to the Cullinan Diamond Mine operations, it was decided to transport an innovative concrete product down a 714 m borehole through a vertically suspended 150 NB schedule XXS pipeline to the underground workings.

The concrete product batching and delivery system would be operated from surface as opposed to the current underground batching systems. The operation includes an automated surface batching plant, which delivers the concrete product through the suspended pipelines down the borehole to an underground storage facility from where the product gets delivered to the working area by further pumping or agicars.

In order to ensure the integrity of the suspended pipe ranges, a stress analysis of the pipelines was conducted for the expected temperature extremes to ensure that the applied pre-tension guaranteed that the columns remain in tension.

The loads from the pipe stress analysis were then used in a finite element analysis of the coupling connectors to determine the internal stresses under the various load conditions.

Finally a fatigue analysis of the system was undertaken to evaluate the effect of local stress raisers within the threaded coupling.

The data generated from the pipe stress and finite element analyses were ultimately used to design the top and bottom bearers and to dictate the critical aspects of the installation procedure.

Introduction

The De Beers Cullinan Diamond Mine is situated north-east of Pretoria in the Gauteng province of South Africa. The mine is a mechanized underground operation beneath an open pit. The mining method is block cave mining in the existing block with an advanced undercut mining method for the new BB1 East Advanced Undercut Block. This mining method will serve as a testing ground of the future Centenary Cut Block from where diamonds will be mined at 1 000 m below surface.

The mining haulages and undercut operations are supported by a combination of rock sealant to prevent the ingress of water with bolts and meshing or strapping, which is then covered in a layer of wet or dry shotcrete.

The tunnel roadways are to be concreted with 45 MPa concrete with 60 MPa concrete being utilized in the ore passes and at the drawpoints beneath the undercut level.

The current mining operation utilizes underground batching plants, with dry aggregates and cementitious binder being dropped down through ore passes and pipelines to the underground batching plants. The required concrete product is batched and transported to the utilization site in agicars.

With the advent of the BB1 East Advanced Undercut and the Centenary Cut, the demand for concrete and shotcrete is to increase significantly, and the decision was made to review various options for increasing concrete production.

The first option was to upgrade the underground operations and drill more aggregate passes from surface to additional batching plants underground. Two more options were considered, with both options involving a surface batch plant and piping down either the available shaft structures or through a borehole. The shaft options were discarded based on the risk of pipeline failure in the shafts and the lack of experience with concrete transportation through pipelines. The borehole pipeline option was also initially discarded in favour of more aggregate passes

Drilling began on the aggregate passes to underground batch plants; however, due to water ingress and the instability of the virgin rock, this approach was abandoned in favour of a borehole routed pipeline. The shaft routed systems were again rejected on risk.

The operating philosophy behind the borehole pipeline was to ensure that the pipeline remained full with concrete to the collar, and this system is commonly referred to

* *NS Consultancy.*

† *Murray and Roberts Cementation.*

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as a 'full flow' system in the backfilling industry. Simply put, a 'full flow' system requires that the frictional losses generated by the specific concrete product flowing through the pipeline be balanced against the available head due to the depth to which the product is delivered underground.

The ramification of this pipeline requirement is that the batch plant output must match the discharge from the end of the pipeline into the underground storage system.

The main criterion for the borehole option was that it was going to be made sufficiently large to provide ventilation of the underground workings as well. This implied that the pipeline would have to be suspended from surface as it could not be grouted in or connected to a steel framework within the borehole.

Because of the dynamic loading that the pipeline may experience with such a dense material being transported through it and the delivery pump having an associated harmonic, it was decided to rigidly fasten the pipeline on surface and underground. This meant that the pipeline installation had to be rigorously investigated as to the stress regimes to which it would be exposed.

Pipe stress analysis

Modelling

The 714 metre long 150 NB suspended pipe column was modelled with the Caesar II pipe stress analysis software. The column consists of 9.144 metre long lengths of pipe that are joined with screwed couplings which are butt welded to the ends of the pipe. The column is lowered down from a top bearer on surface and attached to the bearer at the bottom of the borehole. The column is then pulled up in order to introduce pre-tension into the column. No intermediate supports are used between the supporting bearers.

The deflection of the top and bottom bearers varies during the different stages of installation and during operation of the column. Figure 1 illustrates the different stages of deflection of the top and bottom bearers.

The bearers are subjected to five different stages of deflection. Upward movement is defined as positive:

- Stage 1 is the non-deflected bearers (D_{nl}).
- Stage 2 is the deflection of the top bearer due to the

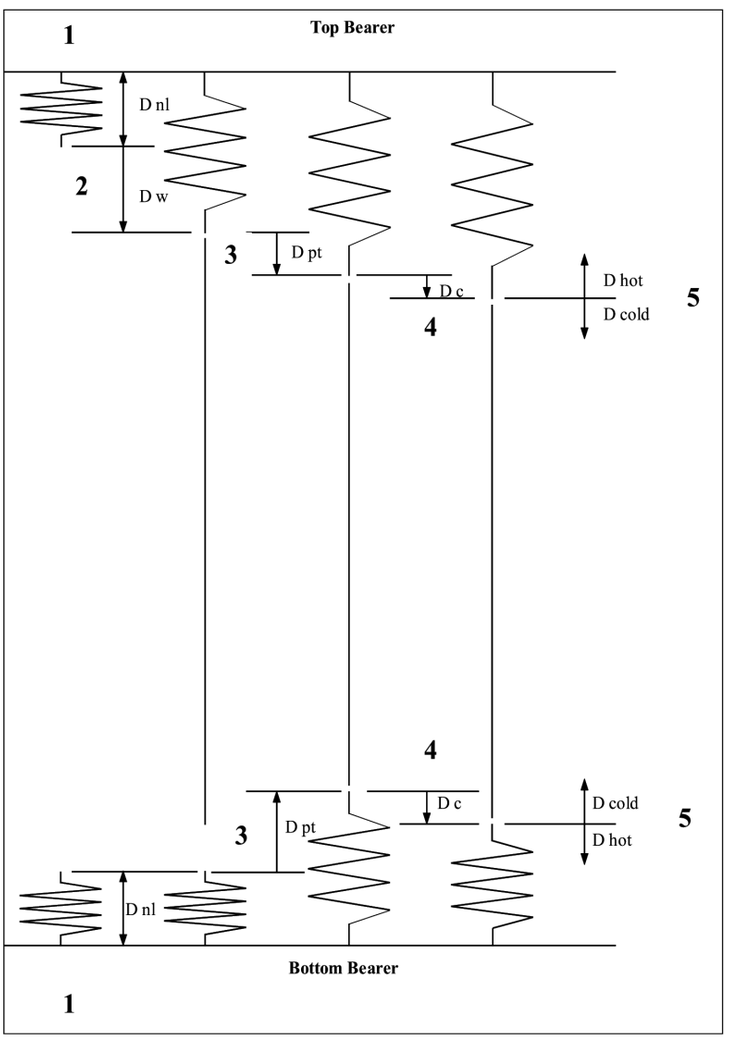

Figure 1—Stages of bearer deflection

empty weight of the column and the couplings (D_w). Note that the bottom bearer does is not subjected to any sustained loading at this stage.

- Stage 3 is the deflection of the top and bottom bearers due to pre-tension (D_{pt}).
- Stage 4 is the deflection due to the weight of the concrete in the column (D_c). The weight of the concrete was assumed to be shared equally between the top and bottom bearers.
- Stage 5 is the deflection of the bearers due to the thermal expansion or contraction of the column.

During installation, the column is lowered from the top bearer down the borehole to the bottom bearer. The mass of the empty column is always supported by the top bearer. The column elongates due to its self-weight as it is lowered down until it reaches the bottom bearer to which it is connected. The bottom bearer should not support any of the weight of the column. Once attached to the bottom bearer, the column is pulled up to apply a pre-tension into the column.

At this stage the column is connected to the top and bottom bearers and under pre-tension. If the bearers are treated as rigid members, the top bearer always carries the weight of the empty column. If the bearers are treated as flexible members, they would defect under load and the weight of the column would be shared between the top and bottom bearers.

Thermal contraction of the column increases the tension in the column whereas thermal expansion would tend to lengthen the column and cause it to bow if there was no pre-tension in the column. Thermal changes produce a variation of stress in the column and couplings but the column should always remain in tension.

For the pipe stress analysis, the 714 metre long column was modelled as having 698.6 metres of plain pipe followed by a 15.9 metre long rigid element with a mass of 2 388 kg to represent the couplings.

The bottom bearer was then attached to a 'cut short' element, which was inserted below the rigid element. The cut short element allows for the modelling of cold spring. The cut short element was used both to remove the suspended mass of the empty pipe column from off the bottom bearer and to apply pre-tension into the column.

A dimension of 217.743 mm was input for the cut short element with 100.143 mm accounting for the elongation of the column due to its self weight and the remaining 117.6 mm being used to apply the pre-tension into the column.

Bearer loading

The decision was made to treat the top and bottom bearers as rigid members.

Figure 2 represents the various load vectors applied to the top and bottom bearers for the suspended column. The loads for three (3) suspended columns have been indicated and have been divided into separate categories as listed in the bottom right of the figure.

The following notes apply to Figure 2.

- The bearers are treated as rigid members with no deflection or load sharing between the bearers
- Only the top bearer should support the empty weight of each column
- A 12.5% pipe mill tolerance and 2 mm corrosion allowance has been incorporated into the stress and load calculations as required by ASME B31.3 Piping Code
- The bottom bearer was assumed to fully support the weight of the pipe content
- A 10 MPa supply pressure is to be provided at the discharge of the surface pump
- The calculation of the transient or water hammer pressure (Pw) has been calculated using the Joukowski[a] formula
- The direction of the load due to pipe content on the bottom bearer is opposed to that of the thermal (contraction) and pre-tension loads and should not be summed together
- The direction of the pressure and occasional loads are opposed to the sustained and thermal (contraction) loads and should not be added together
- A temperature differential of 14.1 degrees Celsius below the ambient temperature of 21.1 degrees Celsius has been applied to the column
- A cold spring or pre-tension of 117.6 mm has been included in each column
- The mass of the pipe content could also be added to the top bearer as a safety measure
- It is possible for a maximum of 2 columns to be filled at any one time and would occur only if there were a failure or blockage in one of the columns
- Bearers should be designed to support the maximum loads and the most conservative approach of load combination is recommended.

Table I lists the stresses for three different load cases in the section of pipe located directly below the top bearer. The highest expected tensile load on the coupling is expected to be 126 tonnes.

The thermal loads presented on Figure 2 are those obtained with an average column temperature of 7°C. The assumption of rigid bearers prevents any pressure induced longitudinal stresses from occurring in the pre-tensioned section of the column. Any shortening of the column due to the Poisson effect has also been neglected.

[a] *Joukowski formula used to determine peak transient pressure (Pw) where:*
Pw = Density × Celerity × Velocity with Velocity = 2.5 m/s, Density = 2300 kg/m³ and Celerity = 1350 m/s where Celerity is the speed of the pressure wave travelling along the pipe.

Table I

Stress variation in the suspended column just below the top bearer

Load case	Load tonnes	Stress MPa	% of allowable
Self weight	-58.2	60.77	44.1
Self weight + cold spring	-93.4	97.90	64.5
Self weight + cold spring + tmin	-126.0	132.35	87.3

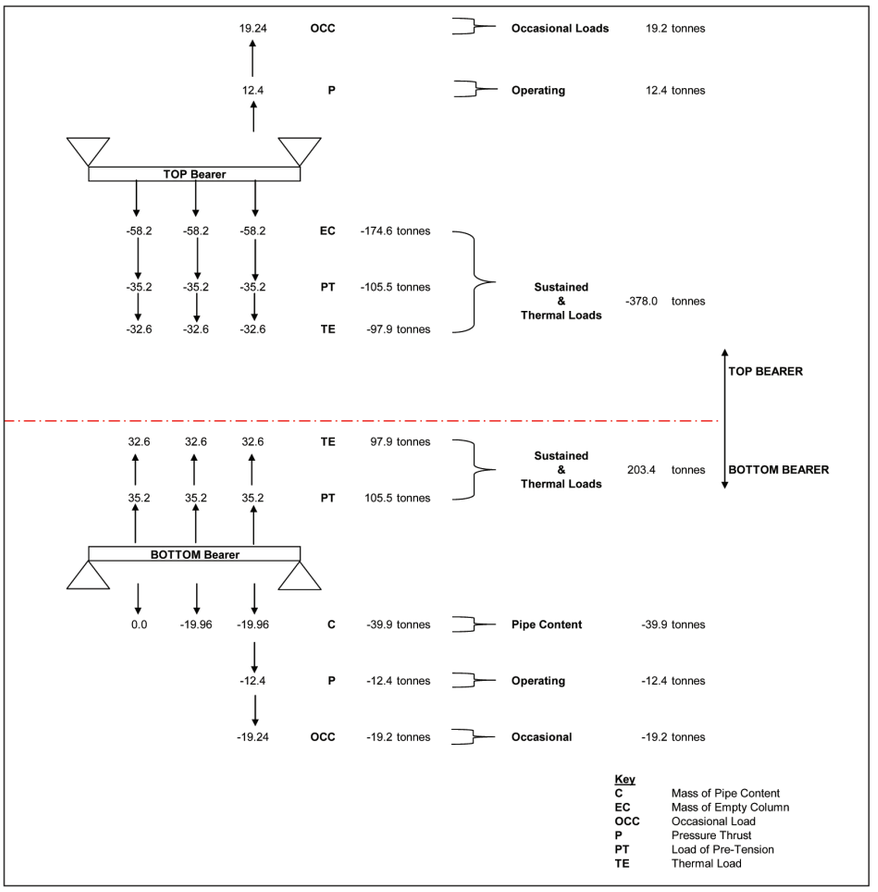

Figure 2—Loading schematic for the top and bottom bearers of the suspended column

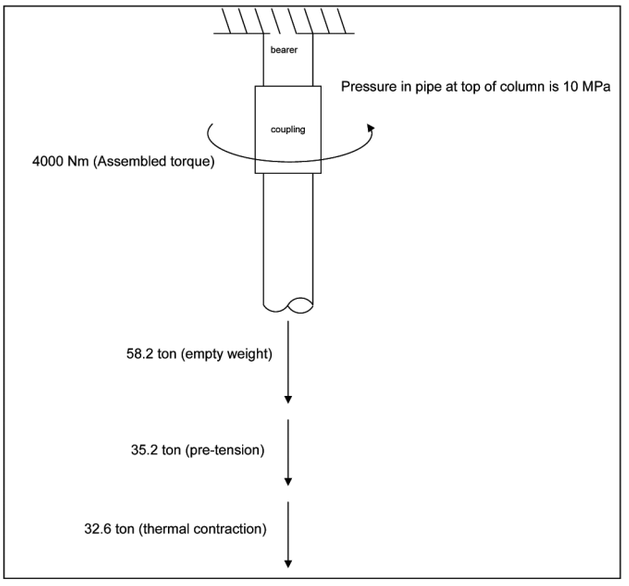

Figure 3—Loads utilized in the finite element analysis of the screwed coupling

Figure 3 presents the loads used in the Finite Element Analysis of the screwed coupling. The supply pressure of 10 MPa is provided by the pump on surface, which delivers concrete to the borehole column. At the bottom of the column, the pressure increases to 25.4 MPa.

At the first coupling below the top bearer, the vertical loads and the applied torque during assembly generate tensile stresses and thread contact stresses in the coupling. The internal pressure would produce only hoop stresses, with the longitudinal stress being eliminated because of the rigidity of the bearers.

Installation loading

The two important aspects of the installation are to ensure that the weight of the empty column is entirely supported by the top bearer and secondly that the amount of pre-tension applied to the column is able to be controlled.

The first prerequisite is achieved by lowering the column slowly into its point of attachment on the bottom bearer. The pipeline is then connected to the bottom bearer after which the column is pre-tensioned by pulling the pipeline back towards the top bearer. A rigger on the level at the bottom bearer must be able to control the rate of descent of the column from surface and ensure that it is done slowly. This is to prevent the pipeline from coming into contact with anything at the bottom of the borehole. The pipeline would buckle easily if it is lowered too quickly and makes contact with either the bottom bearer or the footwall. Once the connection to the bottom bearer has been made, the column must not be allowed to be lowered or slip down any further.

Determination of the amount of pre-tension being applied to the column can be carried out in two ways. The first is to measure the distance that the column is stretched up once it has been connected to the bottom bearer. The advantage of this method is that it is direct and simple, but it may not be very accurate because any clearances or deflections of the bearers will affect the level of pre-tension and it is highly likely that the amount of pre-tension would be lower than what was designed for. The pre-tension in one of the columns will be reduced once the pre-tension is applied to the second or third column. Once all the clearance has been taken up, the column should be pulled up by 117 mm to achieve the required amount of pre-tension.

The most effective way to apply the pre-tension would be to utilize a load cell that is integrated into the column. Ideally the load cell should be able to differentiate between the various loading stages and be able to provide continuous monitoring of the column. The most information would be obtained from the load cell if it were located at the top of the column. If the load cell is to be used only to determine the level of pre-tension, then it would be best to position it at the bottom of the column.

The use of the load cell is highly recommended. The output from the load cell could provide the sustained, operating and thermal loading in the column and could also be used to monitor the fatigue life of the column and trigger alarms if the loads exceeded a predetermined limit. The load cell could also be monitored while delivering concrete to indicate if shock loads are being transferred to the column.

The load cell at the top of the column should read 93.4 tons once the column has been pre-tensioned. The load of the suspended empty mass of the column should be recorded just prior to the column being attached to the bottom bearer.

A load cell positioned at the base of the column should read 35.2 tons after pre-tension.

Allowance must be made to apply more pre-tension to the column if a second or third column is installed and pre-tensioned. This may cause the bearers to deflect and reduce the levels of pre-tension in the columns that have already been installed and pre-tensioned.

Finite element analysis

Modelling

The screwed coupling was modelled in detail using finite element methods. Both an axis-symmetric model and a 3D model of the coupling were produced. The 3D model required long computational times and the analysis was carried out using the axis-symmetric model.

By the time that the FEA was conducted, the couplings had already been manufactured and had been welded to the pipes and nothing could be done to reduce the levels of stress concentration or localized plasticity that would occur under conditions of full load. Due to the machining tolerance, the radii could be expected to vary from between 0.35 and 0.5 mm and the decision was made to utilize the smaller radius of 0.35 mm throughout the model of the coupling to obtain the largest values of stress concentration.

Figure 4 illustrates how the coupling is comprised of a male and female component where the ends are butt welded to the pipes (not shown). Both the threaded portions of the coupling and the non-threaded sections with a fillet radius are clearly seen.

The area of the coupling exposed to the highest stress concentration and localized plasticity has also been highlighted. Although not able to be seen from Figure 4, the coupling has been modelled in detail and the mesh density was increased in the areas at the root of the threads and the fillet radii as these were areas where high stresses could be expected.

Figure 5 shows the von Mises stresses in the coupling for the load cases indicated in Figure 3.

Figure 6 indicates the stress raisers in the coupling with the highest stress levels occurring in the section of the coupling highlighted in Figure 4.

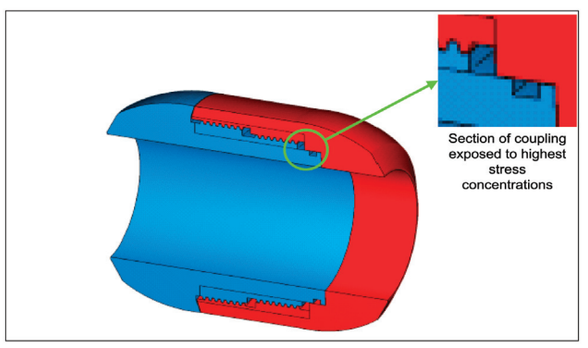

Figure 4—Assembled coupling showing male (in blue) and female (in red) components

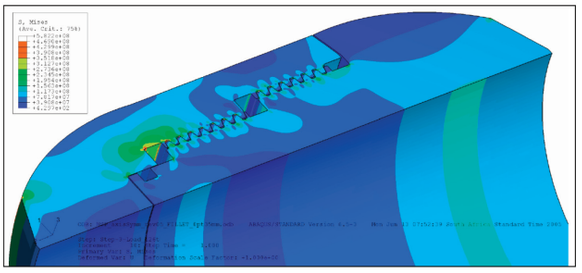

Figure 5—von Mises stress in coupling

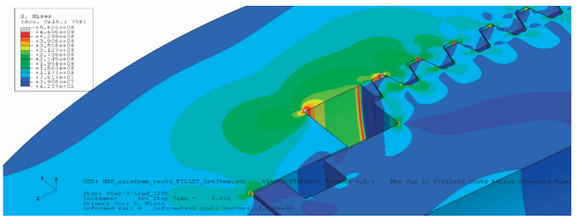

Figure 6—Enlarged contour of von Mises stress in coupling

Results of the FEA

The primary cause of stress variations in the pre-tensioned column are due to temperature variations that cause the column to expand or contract. The maximum principal stresses and strains were obtained from the FEA model for the temperature ranges that could be expected during summer and winter seasons. These results are given in Table II. The values of principal strain were then input into a constant amplitude strain life fatigue analysis to determine the working life of the coupling.

The results of the FEA indicated:

- The localized stresses in the threaded root areas exceeded the 469 MPa yield stress of the coupling material resulting in a region of localised plasticity
- The region of localized plasticity remains small.

Under static conditions where the pipeline would remain in constant tension without any thermal induced loading, the localized plasticity would be inconsequential. However, the pipeline is a dynamic system due to the variation in temperature gradient over 24 hours, hot day to cold night and cold day to freezing night over the year.

Under these conditions the pipeline flexes daily or goes through a daily expansion and contraction cycle. This means that the pipeline fatigues in the region where localized plasticity has occurred. This made it necessary to conduct a strain life constant amplitude fatigue analysis to determine the expected life of the coupling.

Fatigue analysis

One of the foremost authorities on fatigue is Dr. Darrell Socie[b]. He has a program for the analysis of the fatigue life of a component based on its physical properties and operating conditions. He was both consulted and his method of analysis used to evaluate a fatigue life of the coupling.

Due to the fatigue being strain dominant, a strain life analysis was carried out.

A concentration factor of 1 was utilized because the strain values were obtained directly from the FEA model. A plasticity correction was made to the stresses before computing the fatigue life using Neubers Rule, which is used to convert an elastically computed stress or stain into the real stress or strain when plastic deformation occurs.

This plasticity correction is part of the fatigue analysis model. The material properties for the strain life and cyclic stress strain curves were selected from a database contained in the fatigue model. In this case, an AISI steel 1020 was used owing to the comparative carbon content with the ST 52 material of the coupling but changed the Young's Modulus to 210 GPa and the ultimate tensile stress to 690 MPa as per the coupling material test certificate.

The model was then run and the result are given below.

Results of the fatigue analysis

The following input parameters were entered into the fatigue life calculator for the coupling material selection:

[b] *Darrell F. Socie, Professor Emeritus of Mechanical Engineering, University of Illinois at Urbana-Champaign.*

Table II

Maximum principal stresses and strains for the different load cases

Season	Case	Ambient temperature °C	Column temperature °C	Suspended mass ton	Pre-tension ton	Thermal load ton	Total load ton	Max principal stress MPa	Max principal strain m/m
Summer	Hot	24	35	57.57	29.31	-27.621	59.259	415.473	0.002173980
Summer	Cold	24	15	57.57	29.31	22.599	109.479	473.515	0.005218750
Winter	Hot	24	24	57.57	29.31	0	86.88	478.326	0.003644860
Winter	Cold	24	2	57.57	29.31	55.24	142.12	475.921	0.007851660

Steel 1020

s_f' = 883 MPa

b = -0.118

e_f' = 0.16

c = -0.412

E = 210000 MPa

n' = 0.283

K_p = 1441 MPa

K_t = 1

S_u = 690 MPa

The calculated life from the input data for the summer cycle was 84 000 cycles to failure. The following strain data from the FEA for the summer cycle was input into the fatigue life calculator:

e_{max} = 0.005218750 mm/mm

e_{min} = 0.002173980 mm/mm

which produced the following results:

N_f = 84 000 cycles

N_{FL} = 20 000 000 reversals

S_{FL} = 121.5 MPa

Δe = 0.003045

e_m = 0.003696

S_{max} = 297.7 MPa

S_{min} = -64.91 MPa

s_{max} = 300 MPa

$\Delta\sigma$ = 360 MPa

e_{max} = 0.005219

$\Delta\varepsilon$ = 0.003045

The result gives the 230-year life span based on a cycle per day during summer.

The equivalent data for the winter cycle is or 26 000 cycles giving 71 years.

The strain data from the FEA for the winter cycle was input into the fatigue life calculator:

e_{max} = 0.007851660 mm/mm

e_{min} = 0.003644860 mm/mm

which produced the following results:

N_f = 26 000 cycles

N_{FL} = 20 000 000 reversals

S_{FL} = 121.5 MPa

Δe = 0.004207

e_m = 0.005748

S_{max} = 342.3 MPa

S_{min} = -77.39 MPa

S_{max} = 340 MPa

$\Delta\sigma$ = 420 MPa

e_{max} = 0.007852

$\Delta\varepsilon$ = 0.004207

The fatigue analysis suggests that the Trucking and Engineering coupling will have a minimum life span of 71 years and a maximum life of 230 years based on a smooth coupling fillet and a minimum thread root radius of 0.35 mm.

Acknowledgements

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Nomenclature

b	:	Fatigue strength exponent
c	:	Fatigue ductility exponent
D_c	:	Deflection due to mass of concrete
D_{cold}	:	Deflection due to thermal contraction
D_{hot}	:	Deflection due to thermal expansion
D_{nl}	:	Deflection under no load
D_{pt}	:	Deflection through pre-tension
D_w	:	Deflection due to weight of column
E	:	Young's Modulus
e_f'	:	Fatigue ductility coefficient
e_m	:	Mean strain
e_{max}	:	Maximum principle strain
e_{min}	:	Minimum principle strain
K_b	:	Stiffness of bottom bearer
K_p	:	Cyclic strength coefficient
K_t	:	Stress concentration factor
K_t	:	Stiffness of top bearer
n'	:	Cyclic strain hardening exponent
N_f	:	Fatigue life
N_{FL}	:	Cyclic strength coefficient
s_f'	:	Fatigue strength coefficient
S_{FL}	:	Stress fatigue limit
S_{max}	:	Maximum stress
S_{min}	:	Minimum stress
T_{cold}	:	Low temperature of the pipe
T_{hot}	:	High temperature of pipe
Δe	:	Strain range
$\Delta\sigma$	:	Stress range ◆