

Discard fatigue life of stranded steel wire rope subjected to bending over sheave fatigue

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Abstract – In this study, discard lifetimes of 6×36 Warrington-Seale steel wire ropes subjected to bending over sheave (BoS) fatigue have been determined theoretically and experimentally. Multiple linear regression model has been devised and novel theoretical discard life prediction equation has been presented by using the least square method. The results indicate that there is a powerful correlation between the results obtained by theoretical model and experimental data. The theoretical discard life prediction equation results can be used in the range of specific tensile loads investigated and diameter ratios used with acceptable error when the values of coefficient of determination (r^2) and correlation coefficient (r) are considered.

Key words: Discard fatigue life / stranded steel wire rope / regression analysis

1 Introduction

Steel wire ropes having many wires/strands that wrapped helical to the fibre or wire core are frequently used in elevators, cranes, mine hoistings, bridges, offshore and aerial ropeway systems. Large scale concern is observed into the rope technology area since crucial carrying duty is fulfilled in the installation. There has been great interest in rope technology area since application area of steel wire ropes is vast. In the application area, steel wire ropes are mainly subjected to fatigue since either rope incurs to the altering loads with time such as bridge or repetitive move on the sheaves such as cranes. First fatigue type is tension-tension fatigue where ropes incur to the altering tensile load.

Second fatigue type is BoS fatigue where ropes incur to the repetitive bending combined with static tensile load.

Test machines that include two stress regimes (tension-tension fatigue and BoS fatigue) for steel wire ropes have been shown in Figure 1.

There are great number of investigations have been conducted to identifying effect of BoS fatigue to the lifetime of the steel wire ropes [1–4]. Ridge et al. [1] assessed effects of simulated degradations (wire breaks, abrasive wear, slack wires, slack strands, plastic wear, corrosion,

torsional imbalance) to the BoS fatigue endurance of steel wire ropes. Urchegui et al. [5] examined wear evolution in a 6×19 Seale stranded rope subjected to bending fatigue. Torkar and Arzensek [6] conducted bending fatigue tests of wires located in outer strands of 6×19 Seale rope. Gorbato et al. [7] investigated effects of some parameters (core type of wire rope, lubricant type and tensile load) to the bending fatigue life of 6×36 Warrington-Seale rope with 16 mm diameter. Feyrer's book [8] presented state of art review and experimental test results of steel wire ropes subjected to BoS fatigue. Author examined effects of various parameters (rope core type, lubrication, tensile load, bending length, sheave diameter, zinc coating, sheave geometry and material, side deflection, winding angle) to the BoS fatigue life of steel wire ropes. Giglio and Manes [9] investigated effect of winding angle parameter between rope and sheave to the bending fatigue life of 19×7 non-rotating rope, which may be used in aircraft rescue hoists, that has nineteen strands and each strand has seven wires. Argatov et al. [10] focused on fretting wear degradation during service life of wires of steel wire ropes. Evolution of linear wear scars on the central wire of the core. Custom-made bending over sheave fatigue test bench was used by authors. Authors concluded that endurance reduces approximately same rate along with increase in wear severity, reduction of sheave diameter increases interwire wear severity and contact patches have a significant influence on rope degradation and fatigue life.

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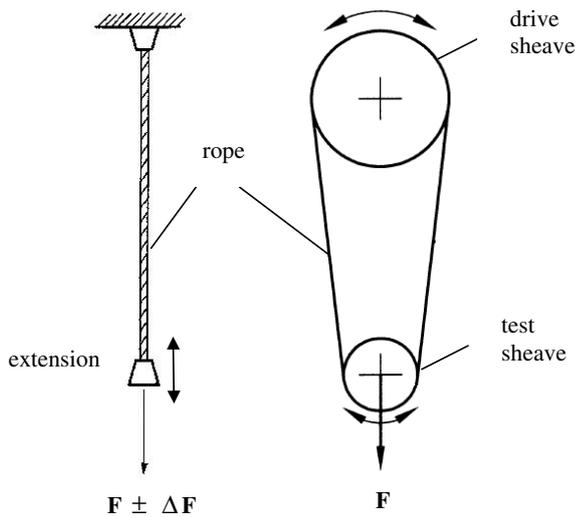


Fig. 1. Test machines: tension-tension fatigue (left) and bending over sheave fatigue (right) [2].

Kurashov et al. [11] performed comparative tests to investigate bending fatigue life of steel wire ropes with various types of core and impregnated with various preservative compounds. Zhihui and Jiquan [12] put effort to improve security and efficiently using of wire ropes and therefore authors discussed fatigue failure behaviors of wire ropes caused by bending over sheave focusing on analysis of mechanisms of wire rope mechanical damage caused by fleet angle and angle of wrap.

Inspection and discarding processes have crucial importance in identifying and taking precaution in rope installations. Degradations such as wire breaks caused by fatigue, wear and corrosion deteriorate rope performance and those cause discard the ropes from service. There is critical degradation extent or amount threshold in which steel wire ropes shall be discarded from service immediately when those critical degradation levels are exceeded. This study enlighten rope users and researchers about discarding cycle or discard lifetime of rope investigated in order to prevent breaking of steel wire ropes causing catastrophic accidents. Thereby article presents one of the most important period to be checked for preventive maintenance. The aim of this study is to determine discard bending over sheave fatigue lifetime of rope investigated experimentally and present novel calculation equation which is extremely important to obtain preventive maintenance cycle period. Eight different tensile loads and two sheaves with different diameters have been employed to determine discard lifetimes (N_A) of 6×36 WS ropes subjected to BoS fatigue. Feyrer equations have been used to predict discard lifetime of 6×36 Warrington-Seale rope subjected to BoS fatigue theoretically. In addition multiple linear regression model has been devised by using experimental test data and novel theoretical discard fatigue life prediction equation has been presented.

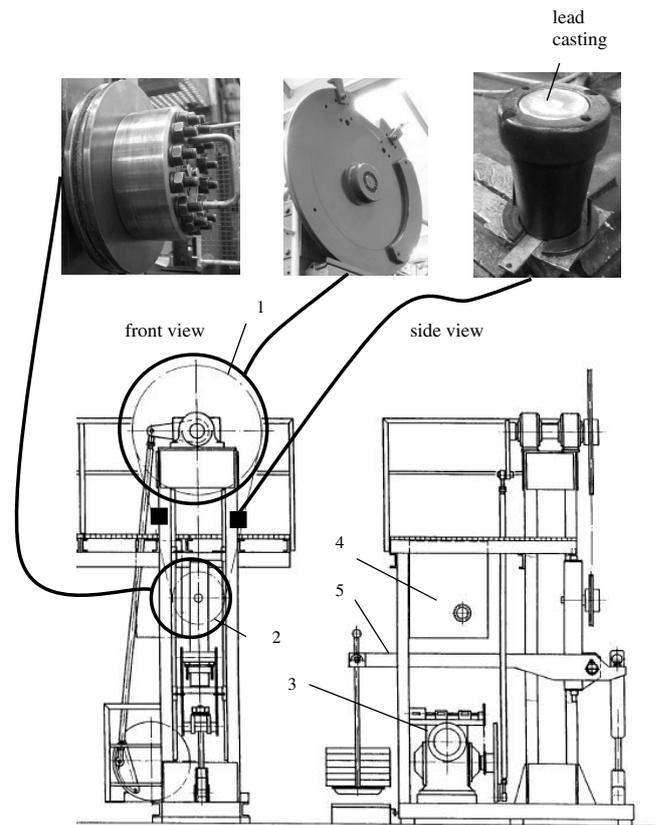


Fig. 2. Bending fatigue test machine [2].

2 Experimental procedure

2.1 Test machine

Experimental tests have been performed in the Rope Technology Laboratory of Institute of Mechanical Handling and Logistics (Institut für Fördertechnik und Logistik (IFT), University of Stuttgart, Germany) so as to exhibit effects of tensile load and sheave diameter to the discard fatigue life of steel wire rope running with sheaves. Test machine is shown in Figure 2.

BoS fatigue test bench comprises of electric motor, test sheave, drive sheave, leverage, rotation speed adjustment button (4) and additional machine elements helping to run. Motor (3) produces the power on test machine. Samples are located between drive sheave (1) and test sheave (2) by means of lead casting end connections. Constant tensile load, S , on the test sheave is maintained by leverage (5) and additional weights in order to simulate real working conditions. Thus, rope samples are loaded by constant tensile during the test. The bigger sheave is drive sheave which drives the rope sample at the certain cyclic length and smaller one is test sheave. BoS fatigue occurs at the contact length between test sheave and rope which is $30d$ in length (d is diameter of rope in mm). Rotation speed was 1250 rev/h for experimental tests [2].

Table 1. Technical properties of 6×36 Warrington-Seale rope [2].

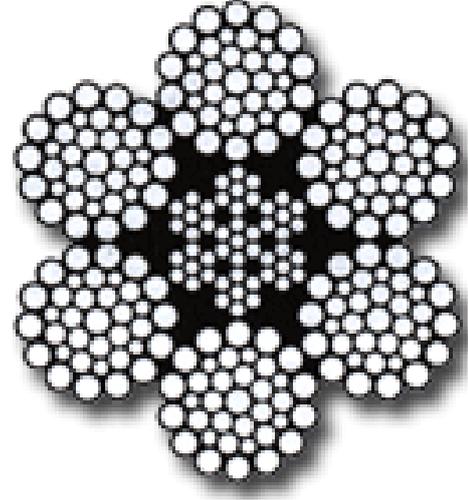
| | |
|-----------------------------|---------------------------------------|
| Strand number | 6 |
| Construction | $6 \times (1-7-7+7-14) + \text{IWRC}$ |
| Diameter | 10 mm |
| Wire grade | 1960 N.mm^{-2} |
| Lay type | Right regular lay (sZ) |
| Filling factor | 0.58 |
| Minimum breaking load (MBL) | 70.4 kN |

2.2 Laboratory measurements

Laboratory measurements during tests have been performed. Condition monitoring is done stopping the test rig in certain periods and rope samples in test are checked whether rope deterioration attain to the one of the discard criteria or not. DIN 15020-2 [13] and ISO 4309 [14] regulations offer discard criteria for frequently encountered degradation types of steel wire ropes. According to these standards, steel wire ropes in service are inspected by degradations such as wire breaks, diminution of wire rope diameter, corrosion, abrasive wear, rope deformations and effect of heat. All of rope discard criteria have been condition monitored. All of rope samples have been discarded when number of wire breaks attains to discard level since number of wire breaks is first emergent situation among discard criteria. Standards stipulate that 6×36 Warrington-Seale rope must be discarded from service at the very latest when 7 or more visible wire breaks in $6.d$ (d is diameter of rope in mm) bending length or 14 or more visible wire breaks in $30.d$ bending length for $1E_m$, $1D_m$, $1C_m$, $1B_m$, $1A_m$ drive groups. Investigated rope is supposed to be operated by indicated drive groups. Drive group grading is made according to load collectives and running time categories. Load collectives take the relative level of the loading or the frequency of full load occurrence into consideration. As regards the grading into running time categories, the mean running time per day related to one year is the determining factor. Discard lifetimes (N_A) of 6×36 WS ropes subjected to BoS fatigue are read by counter device when discard numbers of wire breaks occur in simple bending cycles.

2.3 Investigated rope

Investigated steel wire rope construction is 6×36 Warrington-Seale (WS) rope with Independent Wire Rope Core (IWRC). Rope samples with 10 mm in diameter (d) have been used. Characteristic properties of rope samples are given in Table 1. Investigated rope construction has six strands around a steel core which is a wire rope itself. 6×36 Warrington-Seale rope with IWRC can be used by mine hoisting, oil industry, cranes etc. 6×36 Warrington-Seale rope construction offers optimum resistance in fatigue and crushing. Cross-section of 6×36 Warrington-Seale rope with IWRC used in this study is shown in Figure 3.

**Fig. 3.** Cross section of rope sample used: 6×36 Warrington-Seale with IWRC [2].

2.4 Bending over sheave fatigue tests

BoS fatigue tests have been conducted by using test rig depicted in Figure 2. Rope samples were moulded by lead casting cones on each end and connected to backing rope so as to form a loop which is necessary for the test [2]. In this study, eight different tensile loads and two sheaves with different diameters have been employed to determine discard lifetimes (N_A) of 6×36 WS ropes subjected to BoS fatigue. Sheaves with 250 mm and 100 mm in diameters have been used. Four tensile loads corresponded to range between 21.30%–42.61% of minimum breaking load (MBL) of investigated rope which are 15 kN, 20 kN, 25 kN and 30 kN have been employed when sheave with 250 mm in diameter is used and four tensile loads corresponded to range between 14.20%–35.51% of MBL of investigated rope which are 10 kN, 15 kN, 20 kN and 25 kN have been employed when sheave with 100 mm in diameter is used in the BoS fatigue tests.

3 Theoretical investigations

3.1 Feyrer estimation

Theoretical discard life estimations of 6×36 WS ropes subjected to BoS fatigue have been done by using Feyrer equations that are given in Equations (1) and (2). First equation includes specific tensile load (S/d^2), diameter ratio (D/d) parameters and unit tensile load and unit diameter are considered as $S_0 = 1 \text{ N}$, $d_0 = 1 \text{ mm}$ respectively.

$$\log(N_A) = a_0 + a_1 \log\left(\frac{Sd_0^2}{S_0^2 d^2}\right) + a_2 \log\left(\frac{D}{d}\right) + a_4 \log\left(\frac{Sd_0^2}{S_0^2 d^2}\right) \log\left(\frac{D}{d}\right) \quad (1)$$

Table 2. Constants and parameters used for 6×36 Warrington-Seale rope.

| | |
|-----------------------------|-------|
| d (mm) | 10 |
| R_o (N.mm ⁻²) | 1960 |
| l (mm) | 600 |
| a_0 | 0.583 |
| a_1 | 0.377 |
| a_2 | 6.232 |
| a_4 | -1.75 |
| b_0 | 0.633 |
| b_1 | 0.377 |
| b_2 | 6.232 |
| b_3 | -0.32 |
| b_4 | -1.75 |
| b_5 | 1.2 |

Second equation includes specific tensile load, diameter ratio, wire grade (R_o), bending length (l) and rope diameter (d) parameters that are parameters affecting to the rope's lifetime.

$$\begin{aligned} \log(N_A) = & b_0 + b_1 \log\left(\frac{S}{d^2}\right) - 04b_1 \log\left(\frac{R_0}{1770}\right) \\ & + b_2 \log\left(\frac{D}{d}\right) + b_3 \log(d) \\ & + b_4 \log\left(\frac{S}{d^2}\right) \log\left(\frac{D}{d}\right) - 04b_4 \log\left(\frac{D}{d}\right) \\ & \times \log\left(\frac{R_0}{1770}\right) + \frac{1}{b_5 + \log\left(\frac{l}{d}\right)} \end{aligned} \quad (2)$$

The constants (a_i, b_i) produced in Equations (1) and (2) are given in Feyrer's book [8]. Constants and parameters for 6×36 WS rope are given in Table 2.

Feyrer proposes that the numbers of bending cycles calculated by means of using constants in Table 2 are valid for up to a few million bending cycles under the following conditions: the wire rope samples are well-lubricated, the sheaves have steel grooves, groove radius-rope diameter ratio (r/d) is 0.53, there is no side deflection and it is in dry environment. If there are different conditions in operation correction factors must be used to determine final discard lifetime calculation. As a specific condition for 6×36 WS rope investigated there must be an addition correction factor since constants presented in Table 2 are for 8×36 Warrington-Seale rope with IWRC core. Rope investigated in this study has 6 strands so that theoretically predicted results have been corrected by multiplying with 0.81. This correction factor also has been presented in Feyrer's book [8].

3.2 Regression analysis

Regression analysis investigates relation between dependant variable and independent variable(s). The purpose of the regression analysis is to find the best mathematical model definition. In this study, dependent variable is discard lifetime, N_A , of 6×36 WS rope. There

Table 3. Logarithmic test results for 6×36 Warrington-Seale rope.

| $\log(N_{A_i})$ | x_i | y_i | z_i |
|-----------------|-------|-------|-------|
| 4.761 | 2.176 | 1.398 | 3.042 |
| 4.543 | 2.301 | 1.398 | 3.216 |
| 4.513 | 2.398 | 1.398 | 3.352 |
| 4.409 | 2.477 | 1.398 | 3.462 |
| 4.267 | 2 | 1 | 2 |
| 4.116 | 2.176 | 1 | 2.176 |
| 4.080 | 2.301 | 1 | 2.301 |
| 3.600 | 2.398 | 1 | 2.398 |

are two independent variables which are specific tensile load (S/d^2) and diameter ratio (D/d). Since there become multiple independent variables authors propose multiple linear regression model adhering to the Feyrer equations. General form of multiple linear regression model has been shown in Equation (3) [15].

$$\log(N_i) = a_0 + a_1 \log(x_i) + a_2 \log(y_i) + a_3 \log(x_i) \log(y_i) + \varepsilon_i \quad (3)$$

where $N_i = N_{A_i}$ for discard lifetime calculation, a_i 's are constants, x_i is dimensionless specific tensile load $S.d_0^2/S_0.d^2$ (N.mm⁻²), y_i is diameter ratio D/d , ε_i is residual term. To expedite regression analysis progress, Equation (3) can be expressed as Equation (4).

$$\log(N_i) = a_0 + a_1 x_i + a_2 y_i + a_3 z_i + \varepsilon_i \quad (4)$$

where $\log(x_i) = x_i$, $\log(y_i) = y_i$ and $\log(x_i) \cdot \log(y_i) = z_i$.

To constitute a novel theoretical prediction equation authors used the least square method. The least square method is the one of the most convenient method for curve fitting. The best fit in the least square method means that minimize the sum of squared residuals. Minimum of the sum of residual squares is found by resolving the gradient and equalizing them to zero. Four equations can be obtained including consecutive sum of the terms containing N_i, x_i, y_i and z_i . Final equation set is given in Equation (5).

$$\begin{aligned} \sum_{i=1}^n \log(N_i) &= a_0 n + a_1 \sum_{i=1}^n x_i + a_2 \sum_{i=1}^n y_i + a_3 \sum_{i=1}^n z_i \\ \sum_{i=1}^n x_i \log(N_i) &= a_0 \sum_{i=1}^n x_i + a_1 \sum_{i=1}^n x_i^2 + a_2 \sum_{i=1}^n x_i y_i + a_3 \sum_{i=1}^n x_i z_i \\ \sum_{i=1}^n y_i \log(N_i) &= a_0 \sum_{i=1}^n y_i + a_1 \sum_{i=1}^n x_i y_i + a_2 \sum_{i=1}^n y_i^2 + a_3 \sum_{i=1}^n y_i z_i \\ \sum_{i=1}^n z_i \log(N_i) &= a_0 \sum_{i=1}^n z_i + a_1 \sum_{i=1}^n x_i z_i + a_2 \sum_{i=1}^n y_i z_i + a_3 \sum_{i=1}^n z_i^2 \end{aligned} \quad (5)$$

where n is the number of experiments.

Thus a_i terms can be found by solving Equation (3). The experimental results are shown in Table 3. These experimental results have been used to determine constants. Consecutive sum of the terms containing N_i, x_i, y_i and

Table 4. Consecutive sum of the terms.

| | | | | | |
|--------------------------|----------------|----------------|----------------------|--------------------------|--------------------------|
| $\sum x_i$ | $\sum y_i$ | $\sum z_i$ | $\sum x_i^2$ | $\sum y_i^2$ | $\sum z_i^2$ |
| 18.227 | 9.592 | 21.947 | 41.69549 | 11.81762 | 62.59775 |
| $\sum x_i y_i$ | $\sum x_i z_i$ | $\sum y_i z_i$ | $\sum \log(N_{A_i})$ | $\sum x_i \log(N_{A_i})$ | $\sum y_i \log(N_{A_i})$ |
| 21.9491 | 50.41286 | 27.14966 | 34.289 | 78.06794 | 41.54295 |
| $\sum z_i \log(N_{A_i})$ | | | | | |
| 94.99608 | | | | | |

Table 5. Experimental discard lifetime results for 6 × 36 Warrington-Seale rope.

| 6 × 36 Warrington-Seale rope | | | |
|------------------------------|----------------|-----------------------------|----------------|
| $D = 250$ mm ($D/d = 25$) | | $D = 100$ mm ($D/d = 10$) | |
| Tensile load | N_A (cycles) | Tensile load | N_A (cycles) |
| $S = 15$ kN | 57 702 | $S = 10$ kN | 18 503 |
| $S = 20$ kN | 34 986 | $S = 15$ kN | 13 060 |
| $S = 25$ kN | 32 608 | $S = 20$ kN | 12 038 |
| $S = 30$ kN | 25 672 | $S = 25$ kN | 3983 |

z_i is given in Table 4. The novel theoretical prediction equation by using the least square method is given in Equation (6).

$$\log(N_A) = 7.4996 - 2.3317 \cdot \log\left(\frac{S}{d^2}\right) - 0.2643 \cdot \log\left(\frac{D}{d}\right) + 0.8806 \cdot \log\left(\frac{S}{d^2}\right) \cdot \log\left(\frac{D}{d}\right) \quad (6)$$

4 Results and discussion

Experimental tests have been performed in compliance with DIN 15020-2 standard. Discard lifetimes (N_A) of 6 × 36 WS ropes subjected to BoS fatigue have been obtained by reading counter device when discard numbers of wire breaks occur in simple bending cycles. Discard lifetime results of 6 × 36 Warrington-Seale ropes are given in Table 5.

It can be concluded that discard lifetimes of 6 × 36 WS ropes subjected to BoS fatigue reduces as tensile load increases. Discard lifetime reduces 39.36% if tensile load is increased from 15 kN to 20 kN (for $D = 250$ mm). Discard lifetime reduces 6.79% if tensile load is increased from 20 kN to 25 kN (for $D = 250$ mm). Discard lifetime reduces 21.27% if tensile load is increased from 25 kN to 30 kN (for $D = 250$ mm). Discard lifetime reduces 29.41% if tensile load is increased from 10 kN to 15 kN (for $D = 100$ mm). Discard lifetime reduces 7.82% if tensile load is increased from 15 kN to 20 kN (for $D = 100$ mm). Discard lifetime reduces 66.91% if tensile load is increased from 20 kN to 25 kN (for $D = 100$ mm). Results also indicate that discard lifetime of 6 × 36 WS rope reduces substantially when the sheave with smaller diameter is used.

In addition to experimental studies Feyrer equations have been used to compare the results obtained by experimental tests. Feyrer’s theoretical estimation results

for same parameter pertained to experimental studies are given in Table 6 where N_{feyrer1} is the theoretical results obtained by using Equation (1), N_{feyrer2} is the theoretical results obtained by using Equation (2). R_0 is wire grade (N.mm²), l is bending length (mm).

It can be observed from Table 6 that Feyrer’s estimation equation presented in Equation (2) for 6 × 36 WS rope gives more reliable results than Equation (1). Feyrer’s second estimation equation (Eq. (2)) includes addition parameters affecting to the rope’s discard lifetime such as rope diameter, bending length and wire grade than Feyrer’s first estimation equation (Eq. (1)). While diameter ratio (D/d) becomes 25 results give more accurate than diameter ratio (D/d) becomes 10 when Equation (2) is used. All of the Feyrer’s theoretical prediction results when Equation (1) is used become lesser than experimental results. Therefore it can be concluded that Feyrer’s theoretical estimation results can be used by acceptable error considering safety requirements.

The results obtained by using novel theoretical prediction equation (Eq. (6)) and the experimental results are given in Table 7.

In statistics, in order to check the validity of the theoretical prediction equation the coefficient of determination (r^2) and correlation coefficient (r) are determined. These coefficients are obtained by using equations reported elsewhere [16]. The coefficient of determination (r^2) and the correlation coefficient (r) have been found as 0.924 and -0.961, respectively. Negative value for the correlation coefficient means that experimental results are direction of descending. There is a powerful correlation between the results obtained by theoretical model presented and the experiment results since the correlation coefficient converges to 1. When correlation coefficient becomes 1 there is absolute perfection. It is impossible in nature.

Theoretical and experimental results including regression analysis results are shown in Figure 4, where Feyrer1 is theoretical results obtained by using Feyrer’s first estimation equation (Eq. (1)). These results are given in Table 6 as N_{feyrer1} , Feyrer2 is theoretical results obtained by using Feyrer’s second estimation equation (Eq. (2)). These results are given in Table 6 as N_{feyrer2} . Theoretical denotes in Figure 4 the results obtained by using author’s theoretical equation. These results have been presented in Table 7 as $N_{A \text{ theoretical}}$.

Table 6. Feyrer’s theoretical estimation results for 6 × 36 Warrington-Seale rope.

| S/d^2 (N.mm ⁻²) | D/d | $R_0/1770$ | l/d | N_{feyrer1} (cycles) | N_{feyrer2} (cycles) | $N_{A\text{test}}$ (cycles) |
|-------------------------------|-------|------------|-------|-------------------------------|-------------------------------|-----------------------------|
| 150 | 25 | 1.1073 | 60 | 50 150 | 63 490 | 57 702 |
| 200 | 25 | 1.1073 | 60 | 27 650 | 35 010 | 34 986 |
| 250 | 25 | 1.1073 | 60 | 17 420 | 22 060 | 32 608 |
| 300 | 25 | 1.1073 | 60 | 11 950 | 15 130 | 25 672 |
| 100 | 10 | 1.1073 | 60 | 9494 | 11 680 | 18 503 |
| 150 | 10 | 1.1073 | 60 | 5438 | 6696 | 13 060 |
| 200 | 10 | 1.1073 | 60 | 3668 | 4511 | 12 038 |
| 250 | 10 | 1.1073 | 60 | 2700 | 3321 | 3983 |

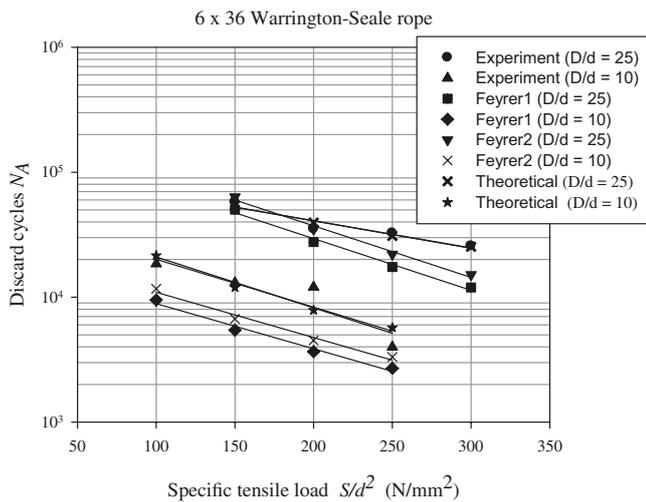


Fig. 4. Theoretical and experimental discard lifetime results of 6 × 36 WS ropes subjected to BoS fatigue (together with regression analysis results).

5 Conclusions

Tensile load and the sheave diameter affect to the discard lifetimes (N_A) of 6 × 36 WS ropes subjected to BoS fatigue substantially. Discard lifetime reduces as tensile load increases. Discard lifetime reduces as the sheave with smaller diameter is used. Feyrer’s theoretical estimation equations can be used by acceptable error considering safety requirements. Presented theoretical prediction equation has powerful correlation with experimental results. Discard lifetime results can be used in the range of specific tensile loads (S/d^2) investigated and diameter ratios (D/d) used with acceptable error when the values of coefficient of determination (r^2) and correlation coefficient (r) are considered.

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Table 7. Theoretical and experimental results for 6 × 36 Warrington-Seale rope.

| S/d^2 (N.mm ⁻²) | D/d | $N_{A\text{theoretical}}$ (cycles) | $N_{A\text{test}}$ (cycles) |
|-------------------------------|-------|------------------------------------|-----------------------------|
| 150 | 25 | 54 325 | 57 702 |
| 200 | 25 | 39 536 | 34 986 |
| 250 | 25 | 30 902 | 32 608 |
| 300 | 25 | 25 292 | 25 672 |
| 100 | 10 | 21 527 | 18 503 |
| 150 | 10 | 11 967 | 13 060 |
| 200 | 10 | 7870 | 12 038 |
| 250 | 10 | 5701 | 3983 |

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