AN EXPERIMENTAL STUDY ON THE RELAXATION OF BOLTS

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ABSTRACT: Loss of pre-load with time, commonly known as 'relaxation' is an established phenomena. Behaviour of a bolted joint depends upon the pre-load in the bolts in use, not the pre-load introduced by the mechanic. Loss of pre-load is expected due to many factors such as embedment relaxation, gasket creep, elastic interactions, and vibration loosening or stress relaxation. In a gasketed joint, due to the gasket flexibility, relaxation in almost all bolts is always substantial during preliminary bolt tightening passes, as 80 to 100% loss is common hence resulting in a dynamic behaviour. It is observed that pre-load in a gasketed joint is controlled to a certain extent only in the final bolt-tightening passes. Experimental study presented in this paper highlights the factors affecting the amount of bolt preload relaxation with time. Important considerations are recommended to reduce bolt relaxation. Both the short and long term relaxations are recorded and a 'best fit' model for relaxation behaviour is derived.

ABSTRAK: Kehilangan prabeban berkadaran dengan masa, atau lebih di kenali sebagai 'Relaksasi' adalah fenomena yang sememangnya wujud. Sifat sambungan bolt bergantung kepada prabeban dalam bolt yang digunakan, bukannya prabeban yang dikenakan terhadapnya. Kehilangan prabeban sememangnya dijangkakan; disebabkan oleh beberapa faktor seperti relaksasi pembenaman, rayapan gasket, saling tindak elastik dan kelonggaran getaran atau tegasan relaksasi. Dalam sambungan bergasket, disebabkan oleh fleksibiliti gasket, relaksasi pada hampir semua bolt sering kali mapan sepanjang pengetatan awal laluan, di mana kekurangan sebanyak 80 ke 100% adalah perkara biasa; seterusnya menghasilkan sifat dinamik. Prabeban pada sambungan gasket dikaji dan dikawal pada peringkat tertentu hanya semasa pengetatan akhir laluan sahaja. Kajian bereksperimen mengetengahkan faktor-faktor penyebab kadar relaksasi prabeban berkadaran dengan masa. Beberapa pertimbangan penting juga dicadangkan untuk mengurangkan relaksasi bolt. Kedua-dua tempoh relaksasi pendek dan panjang telah direkodkan serta model sifat relaksasi yang paling sesuai diperolehi.

KEYWORDS: *preload; bolts; relaxation; experimental; joint; gasketed*

1. INTRODUCTION

From a number of analytical and experimental studies of bolted flanged pipe joints, great importance is attributed to the bolting and assembly of the bolted joints due to different bolt behaviour that can be observed [1-17]. In a gasketed joint, the presence of the gasket and rotation of flanges results in joint relaxation and improper preloading of the bolts. In addition to this, gasket crushing and flange yielding limits higher pre-load [1, 15-34]. Bolt quality and proper tooling has been proven to be important factors in getting proper pre-load in the joint [1]. In this study, pre-loads of 60%, 80% and more than 100% were applied to observe both short and long term relaxations. The bolts were also pre-loaded close to the ultimate tensile strength of the bolt material, to study its relaxation behaviour. This experimental study highlights important factors that affect amount of relaxation in bolts with time and presents important considerations that may be effective in reducing this occurrence. During this study, a bolt calibration unit developed for the measurement of force felt by the bolt was used. Furthermore, both the short and long term relaxations are recorded and a 'best fit' model for relaxation behaviour is derived for different pre-loads. Definitions of relaxation terms are given here for clarity:

Short term relaxation: Most of the relaxation occurs shortly, after the joint has been assembled or at least soon after it has been put into service, due to the number of reasons, such as bolt bending, soft parts (gasket), improper tooling and torquing, bolt quality, non-parallelism of flange joint surfaces, geometric variance and so on.

Long term relaxation: It is generally due to the stress relaxation and vibration loosening. Stress relaxation can be related to the creep, as this is substantial under high temperature applications.

Relaxation measurement: In practice different methods such as application of restarting or breakaway torque, bolt length measurement using ultrasonic extensometers are adopted. However none of these are observed perfect, as it is difficult to measure relaxation.

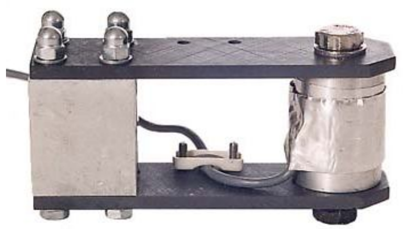
2. EXPERIMENTAL SETUP AND PROCEDURE

A calibration unit consisting of an aluminium cylinder equipped with strain gauges arranged in a Wheatstone full bridge circuit was used for bolt force measurement (Fig. 1a). For better results in recording, an amplifier was also attached with the calibration unit. During the tests, M12 bolts as per ISO-898 grade 8.8 and 10.9 were arranged [35]. Nuts and washers of different thickness and geometry were used in different combinations with these bolts to observe pre-load loss effects. A detailed list of bolts, nuts and washers that were tested is given in Table 1 and the material and strength of the bolts tested are given in Table 2. One bolt from each set was placed in the calibration unit and was applied a given torque using a calibrated electronic torque wrench. Bolts were pre-loaded up to a minimum of 60% (48 kN), 80% (65 kN) and more than 80% (78 kN and 81 kN) of their yield strength or proof load. Pre-load was applied in increments of 10 kN. After each increment the torque reading from the calibrated electronic torque wrench was recorded. After application of the required pre-load, results for the pre-load drop/loss were recorded in the data logging system and were plotted using a pen plotter. In order to observe the effect of re-tightening on pre-load loss, tests were also carried out with bolts that were re-tightened after different time intervals. Experimental set up, tools used, nuts, washers and bolts used are shown in Fig. 1b, Fig. 2a and 2b respectively.

3. DATA PROCESSING

Data recorded during the bolt relaxation was processed using the Power and Logarithmic Function [1] to find the 'best fit' model. Bolt relaxation for each bolt is calculated for the experimental time as well as for 15 seconds to 10 years. During the first

5 minutes a drop of only 1~3 percent was observed. For more than 1 day this value varied for different bolts. Relaxation calculated for all the bolts was nearly the same for the first 24 hours whereas for longer periods it was found to be greater for the logarithmic function than for the Power function. Power function was found to be the **'best fit'** model for the recorded data. Results for the power function are summarized in Table-3 for all the bolts tested. Calculations of these correlation factors also include short term relaxation for the first 1 to 2 minutes as the torque wrench is taken off from the nut. However, neglecting the effect of this initial relaxation, a higher value of correlation factor will be obtained and the pre-load loss or relaxation will be very small, but cannot be neglected.



(a)

(b)

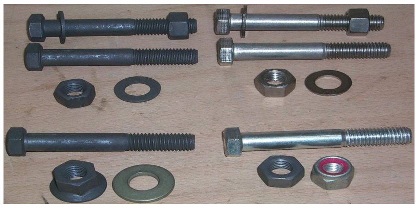
Fig. 1 (a) Calibration unit, (b) Experimental setup.

Table 1: Details of bolts tested for pre-load applied and pre-load loss

Bolt No	Bolt Used	Property Class	Surface Treatment	As per code and marking	Applied Preload (kN)	Re-tightened
2	1st Time	10.9	Wax emulsion	SA A4 316L 100M	66,52,78	Yes
3	1st Time	10.9	Wax emulsion	SA A4 316L 100M	66,52,78	No
4	1st Time	10.9	Wax emulsion	SA A4 316L 100M	66,52,78	No
5,7	1st Time	10.9	Dry lubricant	SA A4 316L 100M	78,81	No
6	1st Time	10.9	Dry lubricant	SA A4 316L 100M	81	Yes
6-LN	1st Time	10.9	Dry lubricant	SA A4 316L 100M	81	No
9	1st Time	8.8	Bright Zinc	ML8.8	81	No
10-LN	2nd Time	8.8	Bright Zinc	ML8.8	60	Yes
10-MK	2nd Time	8.8	Bright Zinc & Molykote	ML8.8	60	Yes
11	1st Time	8.8	Dry lubricant	ML8.8	60	No
12	2nd Time	8.8	Dry lubricant	ML8.8	60	Yes
21 (9)	2nd Time	8.8	Bright Zinc	ML8.8	51	Yes
22 (1)	2nd Time	10.9	Wax emulsion	SA A4 316L 100M	46	No
27 (st)	2nd Time	8.8	Dry lubricant	ML8.8	43	Yes
28 (st)	2nd Time	8.8	Dry lubricant	ML8.8	41	Yes

Table 2: Properties of the bolts tested

Bolt Dia. (mm)	Property Class	Stress Area (mm^2)	Min. Yield Strength (ISO-898)	Proof Load (kN)	Min. UT Load (kN)	Pre-load	
						Recommended (kN)	Based on shank area (kN)
M12	10.9	84.3	900	70.0	87.7	55.0	81.43
M12	8.8	84.3	640	48.9	67.4	39.0	57.91



(a)

(b)

Fig. 2 (a) Bolts, nuts and washers used during tests, (b) Tools (torque wrenches) used.

Table 3: Preload loss with time for all bolts using Best Fit curve

Bolt No.	Time (min)	Correla-tion Factor	Pre-load	A	B	x1	y	y1	Relaxation during		
								Ini. Tor-que	Expe-rimental Time	One day	One year
BLT2	30.0	0.7654	>80 %	54.14	-0.15	0.62	58.27	65.59	11.15	23.35	66.67
BLT2-R1	30.0	0.9278	>80 %	60.44	-0.16	0.64	64.86	65.07	0.33	14.13	63.55
BLT2-R2	30.0	0.9262	>80 %	61.93	-0.15	0.66	65.95	66.20	0.38	13.50	62.24
BLT3	30.0	0.9259	>80 %	49.18	-0.10	0.57	52.05	52.11	0.11	9.79	47.81
BLT4	110.0	0.5793	>80 %	67.39	-0.19	0.67	72.65	74.90	3.00	18.38	70.58
BLT6	70.0	0.7371	>80 %	66.37	-0.70	0.78	78.63	80.80	2.68	45.26	98.68
BLT6-R1	30.0	0.8356	>80 %	70.91	-0.56	0.81	79.99	81.02	1.26	37.13	96.78
BLT6-R2	15.0	0.8734	>80 %	73.84	-0.47	0.83	80.71	81.48	0.94	31.75	94.35
BLT6-LN	120.0	0.6582	>80 %	75.56	-0.04	0.22	80.16	80.79	0.77	7.21	25.91
BLT7	794.0	0.8190	>80 %	51.66	-0.09	0.24	58.41	59.16	1.27	14.26	47.34
BLT9	65.0	0.8812	>80 %	74.16	-0.10	0.50	79.52	80.79	1.57	11.86	49.24
BLT10-LN-R1	22.0	0.9374	>80 %	60.57	-0.71	0.99	61.22	61.49	0.44	39.39	98.49
BLT10-MK	20.0	0.7771	>80 %	48.83	-0.08	0.06	60.94	61.58	1.04	21.10	50.63
BLT10-MK-R1	60.0	0.8933	>80 %	55.83	-0.04	0.07	61.44	61.70	0.42	9.74	26.92
BLT12	72.0	0.6205	>80 %	54.30	-0.30	0.80	58.14	59.24	1.87	23.05	84.28
BLT12-R1	63.0	0.8679	>80 %	57.52	-0.22	0.85	59.66	59.85	0.32	15.91	73.46
BLT21	44.0	0.7520	80%	48.37	-0.02	0.20	49.85	50.68	1.65	4.90	14.59
BLT21-R1	40.0	0.9266	>80 %	48.13	-0.04	0.25	50.76	50.87	0.22	6.18	24.43
BLT22	25.0	0.7622	60%	44.71	-0.17	0.28	55.82	42.26	-32.1	-1.36	62.08
BLT27	20.0	0.7308	80%	34.45	-0.18	0.31	42.46	42.90	1.01	23.37	71.59
BLT27-R1	10.0	0.7162	80%	36.41	-0.17	0.32	44.30	44.40	0.22	21.81	70.23
BLT27-R2	10.0	0.5406	80%	40.45	-0.10	0.33	45.27	45.40	0.28	13.41	50.85
BLT28T	40.0	0.7556	80%	38.68	-0.10	0.70	40.04	40.30	0.64	8.78	45.54
BLT28T-R1	44.0	0.7898	80%	39.57	-0.03	0.76	39.95	40.00	0.12	2.96	19.16
BLT28T-R2	36.0	0.8076	80%	39.59	-0.03	0.72	39.95	40.02	0.16	2.56	16.18
BLT28R	35.0	0.8349	60%	29.34	-0.11	0.78	30.15	30.25	0.32	9.00	49.50
BLT28R-R1	38.0	0.7941	60%	29.94	-0.02	0.83	30.04	31.00	3.09	4.54	13.72

4. RESULTS AND DISCUSSION

Results for different bolts 2-7, 10 and 21 which are plotted in Fig. 3 to Fig. 8, and summarized in Table 3 are discussed below.

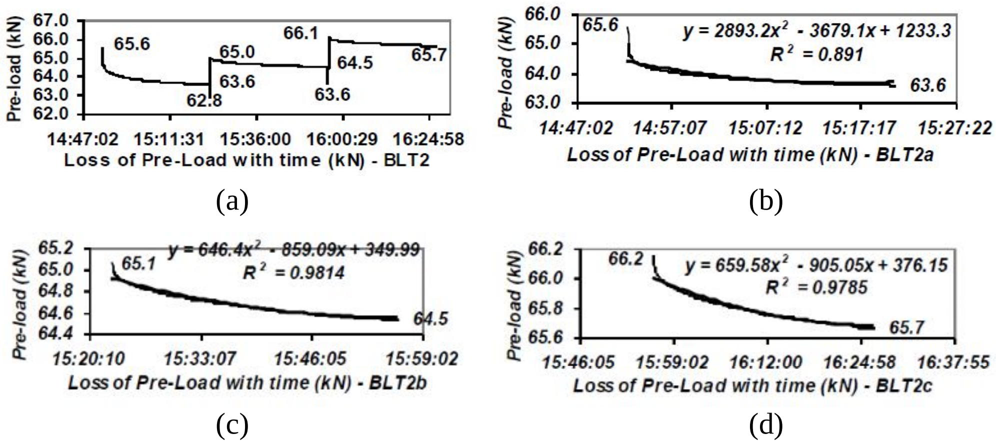


Fig. 3: Loss of Pre-load with Time for Bolt-2. (a) Overall tightening, (b) First tight, (c) First Re-tight, (d) Second Re-tight.

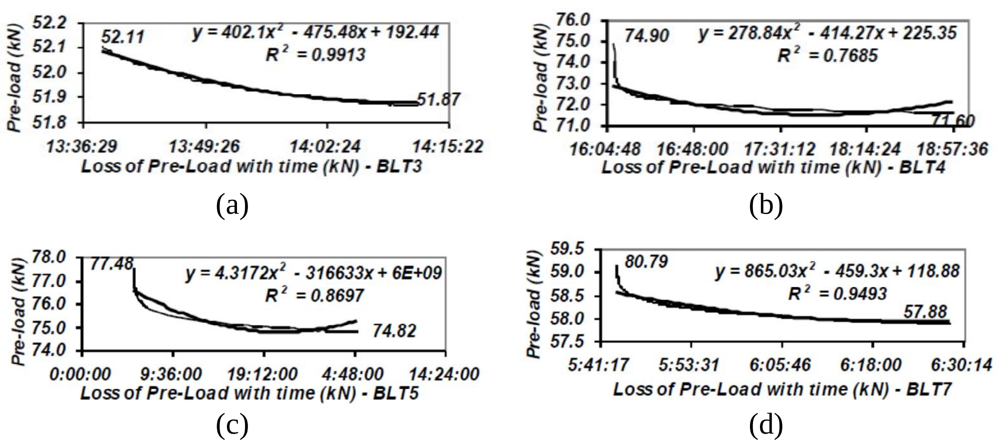


Fig. 4 Loss of Pre-load with Time. (a) Bolt-3, (b) Bolt-4, (c) Bolt-5, (d) Bolt-7.

4.1 Pre-load Above 80% of the Minimum Yield Strength of Bolt Material

During these tests, the bolts were torqued above the recommended value of 80% of bolt yield [1-7]. Pre-load applied is given in Table 2. The purpose was to see its effect on the loss of pre-load. For all the bolts, during the first 1 to 2 minutes a rapid loss of pre-load was observed. This drop was different for different bolts. A variation in pre-load loss of 0.5 to 2 kN was noted which was about 1 to 3 percent of the initially applied torque. This is always expected from the bolt as the torque wrench or hydraulic tensioner is removed from the bolt. After 3 to 4 minutes, steady and continuous pre-load drop behaviour was recorded for all the bolts. All the bolts (BLT1~BLT12) were tested for the first time and results were recorded for different time intervals ranging from 10 minutes to 24 hours. Results were used to obtain the best fit model via curve fitting. Three models, namely the logarithmic, power and exponential models were tried. All were found to be very close to each other. The correlation factor for all the bolts was found ranging from 0.6205 to 0.9252. There were no visible difference in the results of bolts noted for different surface treatments and grades.

4.2 Pre-load of 80% of the Minimum Yield Strength of Bolt Material

The bolts were pre-loaded to the recommended value of 80% of bolt yield [1-7]. Pre-load applied is given in Table 2. A very small drop of pre-load was observed for all the bolts during the first 1 to 2 minutes, which became very steady and nearly negligible. All the bolts (BLT12~BLT28) were tested for the second time and results were recorded for different time intervals ranging from 10 minutes to 24 hours. Results were used to obtain the best fit model via curve fitting. Three models, namely the logarithmic, power and exponential models were tried. All were found to be very close to each other. the correlation factor for all the bolts was found ranging from 0.7308 to 0.9. There were no visible difference in the results of bolts noted for different surface treatments and grades.

4.3 Effect of Lock Nuts and Lubricants

This study was carried out to see the effect of lock-nut and lubricant on the loss of pre-load. Bolt number 6 and 10 were tried with lock-nut for a pre-load of above 80%. It was noted during the test that the proper strength of the Nyloc could not be utilised due to the bolt length. Only two to three threads were utilised. However, the results recorded are presented in graphs for BLT6-LN and BLT-10N. A correlation factor of 0.6582 to 0.6652 was calculated. Bolt BLT10 was used with Molykote lubricant for the pre-load of about 80% and a comparatively good correlation factor of 0.8359 was observed.

4.4 Effect of Re-tightening

Bolt relaxation during the first few seconds or minutes was observed to be rapid as the torque wrench is taken off the nut. However, rapidly it becomes very slow. This study was conducted during the actual situations for the first loading during proof testing and even after first tightening pre-load is reduced. The bolts were re-tightened after different intervals of time to see its effect on bolt relaxation. It was noted that re-tightening has a pronounced effect on the pre-load loss control as also highlighted by Bickford and Abid [1, 13]. Some of the bolts were re-tightened twice after the first tightening. The correlation factor was noted to be higher and an initial pre-load drop was observed.

For some of the bolts, results that were recorded were not found to be good. During re-tightening a smaller correlation factor was observed, e.g. for bolt BLT27 and BLT28R. This was due to a disturbance to the data logging system due to the use of some of the lab machines for routine maintenance. However, from the results plotted on a flat bed plotter and from the recorded results nearly the same behaviour was observed.

4.5 Effect of Tightening Speed and Number of Passes

During the present experimental study, the effect of bolt tightening speed was also found to be important in controlling pre-load loss. It was observed that the bolts that were tightened fast, may not have time to settle in during the tightening process. These may relax more after the tightening procedure. However, during the present study this effect was not recorded and is planned for future studies. In order to compensate for such factors, re-tightening of bolts is strongly recommended [1]. Similarly, tightening of bolts in a series of passes to assemble the joint uniformly, rather than applying full torque on the first pass allows time for relaxation. For both of these reasons, progressive tightening is concluded a virtual necessity on large gasketed joints.

4.6 Proper Tooling and Fastener Dimensions

At the start of experiments, no consideration was given to the tooling required for the bolts. However, it was found that some bolts are of metric dimensions and some were not. Even for the same metric dimensions, nut and bolt heads of different dimensions were observed e.g. for M12 bolt some were observed of 18-mm and some of 19-mm. Different tools available in the lab i.e. conventional torque wrenches, open ring spanners, long handle spanner, electronic calibrated torque wrench were used to highlight the importance of proper tooling to get a required higher pre-load (Fig. 2b). Using conventional ring or open spanners it was found to be very difficult to tighten the bolts and using these tools the bolt head and nut hexagonal geometry were damaged. Sometimes experiments were stopped because of the unavailability of the proper spanner due to the varying dimension of the bolt head or nut. It was also found that the bolts with the same marking have large variation in their quality, geometry, surface finish and other parameters. The bolts used in this study hadvery good quality with proper surface treatment. However torque variation is still observed in the recorded data. It is also observed that the quality of bolts can’t be guaranteed from unknown manufacturers or suppliers. Hence only well known bolt manufacturers should be selected to ensure bolted joint performance for safe joint strength and sealing.

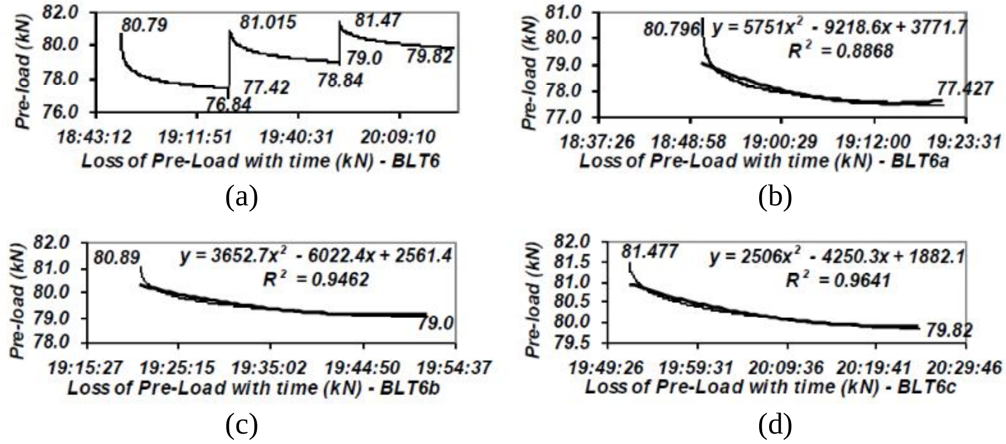


Fig. 5 Loss of Pre-load with Time for Bolt 6. (a) Overall tightening, (b) First tight, (c) First Re-tight, (d) Second Re-tight.

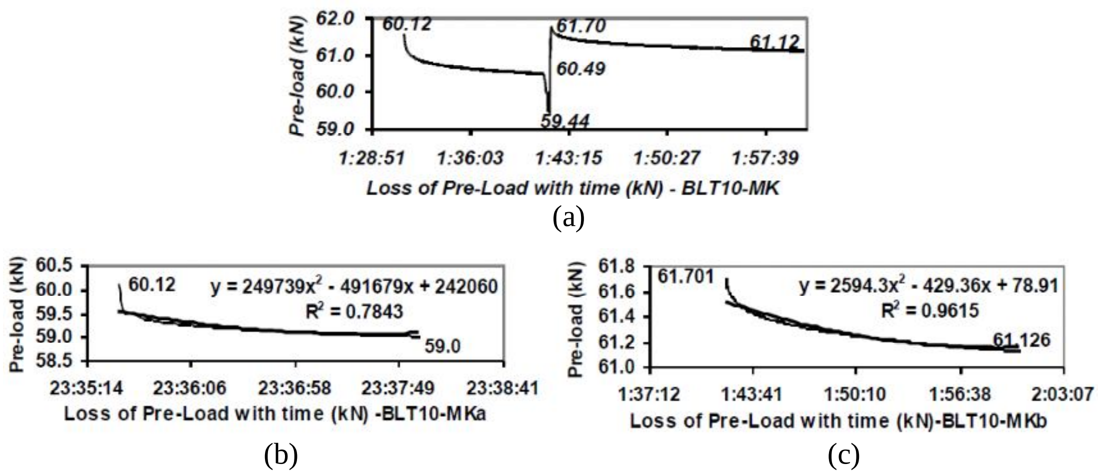


Fig. 6 Loss of Pre-load with Time for Bolt 10 with Molykot lubricant. (a) Overall tightening, (b) First tight, (c) First Re-tight.

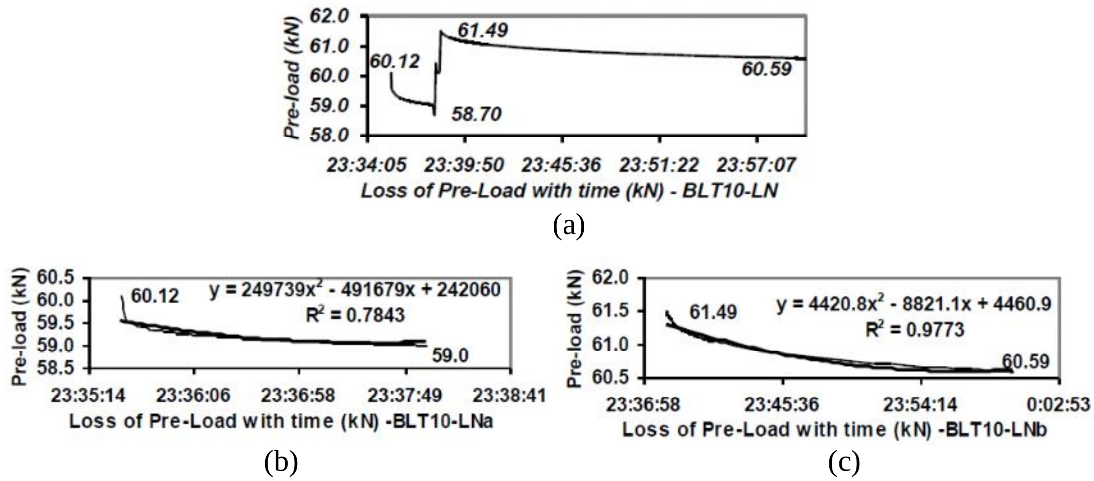


Fig. 7: Loss of Pre-load with Time for Bolt 10 with Locknut. (a) Overall tightening, (b) First tight, (c) First Re-tight.

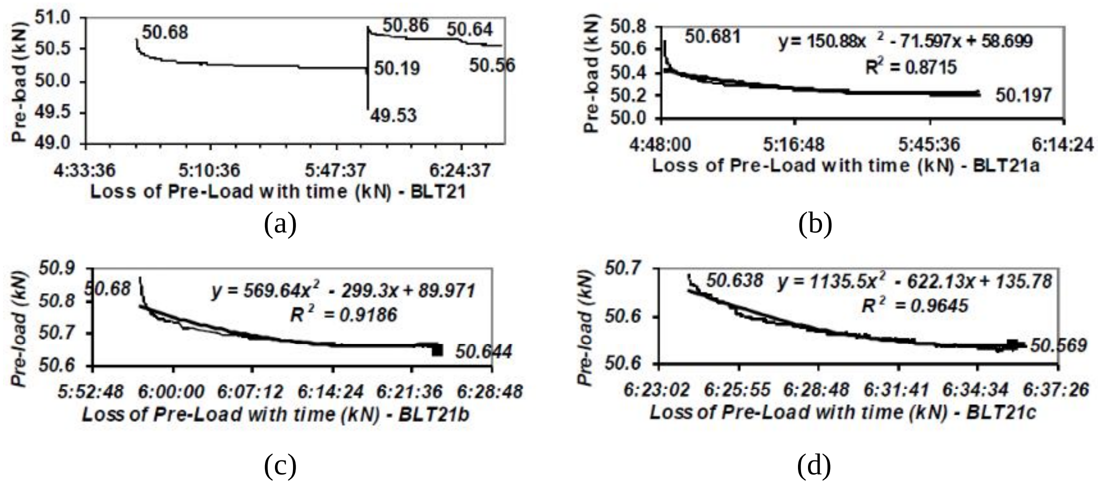


Fig. 8 Loss of Pre-load with Time for Bolt 21. (a) Overall tightening, (b) First tight, (c) First Re-tight, (d) Second Re-tight.

5. CONCLUSIONS AND RECOMMENDATIONS

In light of the results and observations, the following conclusions and recommendations are made;

- Use of new, good quality and high strength bolts with original surface treatment, i.e. dry lubricant, proper bolt tightening speed by properly trained fitters, and with initial higher preload to compensate for the pre-load loss is recommended.
- Use of good quality locknuts and washers and proper tooling, preferably ring spanners instead of open spanners, are recommended.
- Re-tightening of the bolts after a few minutes to several hours and even after proof testing is very important.
- To avoid embedment relaxation, it is recommended that bolts are used after undergoingseveral passes of loosening and tightening. Embedment relaxation may be worse for new bolts.

More than one bolt tightening pass with proper bolt tightening sequence is recommended to achieve uniform preload bolts used in a joint.

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NOMENCLATURE

x	Independent variable
y	Dependent variable
m	Slope of line
a,b	Constants
LN	With Lock-nut (Nyloc)
MK	With lubricant Molykote 321R