European Commission

Research Fund for Coal and Steel

Execution and reliability of slip-resistant connections for steel structures using CS and SS

(SIROCO)

Work package 3: Use of alternative bolts and preloading methods in slip resistant connections

Task 3.2 Use of injection bolts

Draft Final Report

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Contents

FINAL SUMMARY

The RFCS project SIROCO (2014-17) included research on the further development and optimization of double shear connections with injection bolts to achieve slip- and creep-resistant bolted connections considering various influencing parameters. The type of resin, the curing condition of the resin, the geometrical and mechanical characteristics of the connection and the type of loading were studied.
From the research on the behaviour of double shear connections with injection bolts the following main conclusions are:

-The injection procedure is the most important aspect for succesful application. Pot life and viscosity are the most important parameters of a resin.

-The resin mechanical properties show poor correlation with the performance for injected bolted connections.

-The Edilon Dex G 20, the Sika 30 and Sika injection 451 are unsuitable resins for injected bolted connections.

-The Edilon Dex R2K can be applied succesfully but suffers from scatter results and lower strength values compared to RenGel SW404/HY2404.

-The curing temperature of the resin is not a factor for RenGel SW404/HY2404 but is a factor for Edilon Dex R2K.

-From analytical modelling an L/D ratio of 3 is identified as a maximum capacity for injected bolted connections.

-Experimental results show a constant or slightly increasing capacity for L/D ration between 3 and 4.

-A bearing stress of 175 MPa is safely allowable on the long-term without exceeding imposed deformation limits.

-The long term tests also showed that 60% of the initial slip is due to other deformation mechanisms than compression of resin.

-The use of oversize holes reduces the allowable bearing stress as a result of lower initial stiffnes and increased slip as a result of a longer creep length.

-Connections with M36 bolts have the same initial stiffness as M20 connections and a reduced creep deformation at equal loads as a result of lower bearing stress.

2 SCIENTIFIC AND TECHNICAL DESCRIPTION OF THE RESULTS

2.1 Objectives of the project

2.1.1 Brief description and objectives of SIROCO

Slip-resistant connections are required, when deformations in bolted connections must be limited to pre-defined values either for serviceability or ultimate limit reasons. Typical applications can be found in bridges, cranes, radio masts and towers of wind turbines, which are loaded by alternate loading and /or fatigue or where functional requirements make slip-resistant connections necessary. Essential characteristics of these connections are firstly, the level of preload in the bolts and secondly, the slip factor which is mainly influenced by the surface roughness of the clamped plates and – again – by the level of preload. For this reason, the level of preload has to be guaranteed over the whole service life of the structure and loss of preloading due to relaxation and creep effects either because of e. g. geometrical tolerances of the clamped plates or creep due to plastic deformation of applied coatings has to be sure avoided. Whereas slip-resistant connections are already used for carbon steel connections for several decades albeit with high costs, no design and execution rules exist for preloading of stainless steel bolts and subsequently, no slip factors are defined in standards.

Nowadays, the execution standard for steel structures, EN 1090-2, provides rules for the execution of different surface treatments by various classes of friction surfaces for slip-resistant connections. Furthermore, it provides with Annex G a detailed test procedure to determine slip factors taking into account possible creep effects. All rules are valid for carbon steel only. Although the test procedure seems to be very detailed on the first sight, it consists of several uncertainties regarding the test procedure itself and the evaluation criteria which might lead to high costs of testing, underestimation of slip factors and herewith subsequently to unnecessary costs for steel structures and uncertainties about the safety.

The main objectives of the SIROCO project are

- to improve the cost effectiveness of slip-resistant connections made of carbon steel by considering innovative bolts and preloading methods as well as innovative coating systems and closing information gaps for galvanized steel connections and
- to close the lack of knowledge for stainless steel connections with regard to preloading of stainless steel bolts and to the execution of slip-resistant connections made of stainless steel.

The overall study includes the exploitation of design solutions targeting

- an improved test procedure for testing the slip factor,
- innovative preloading methods and coating systems for carbon and stainless steel surfaces to increase the surface roughness,
- development of design rules for preloading of stainless steel bolts and slip-resistant connections made of stainless steel.

The results of the project shall be included in the revisions of EN 1993-1-8 and EN 1993-1-4 for the design of connections made of carbon and stainless steel and in the revision of the execution standard EN 1090-2. All revisions are currently being in process.

2.1.2 Project tree of SIROCO

There are 8 WPs (work packages) which are included in the SIROCO project in total. Each of them has been divided by several tasks. The SIROCO project tree is

- WP1 Test Procedure Slip Factor
- WP2 Long Term Effects (CS)
- **WP3 Alternative Bolts and Preloading Methods (CS)**
  - Task 3.1 Use of lock bolts and H360 bolts
  - **Task 3.2 Use of injection bolts**
  - Task 3.3 Use of Direct Tension Indicators DTI
- WP4 Alternative Surface Treatments and Coatings (CS)
- WP5 Preloading of SS Bolts
- WP6 Slip-Resistant Connections of SS
- WP7 Guidelines and Exploitation Activities
- WP8 Project Management

The title of WP3 is "Use of alternative bolts and preloading methods in slip resistant connections". The main objective of WP 3 is the investigation whether alternative bolts or preloading methods than HV or HR bolts can be used in slip-resistant connections with sufficient reliability.

One of the most promising alternatives is injection bolts. The title of Task 3.2 is "Use of injection bolts", which will be elaborated with detail in this report.

2.1.3 Brief description of injection bolts

Injection bolts are bolts in which the cavity produced by the clearance between the bolt and the wall of the hole is completely filled up with a two component resin. Filling of the clearance of an injection bolt is carried out through a small hole in the head of the bolt. After injection and full curing of the resin, the connection is slip resistant.

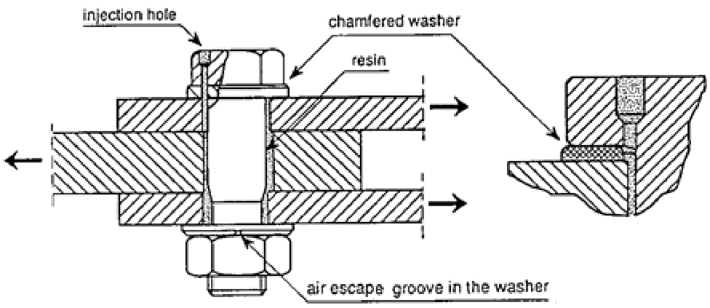


Figure 2.1: Injection bolt in a double lap joint

Injection bolts may be applied in shear connections as an alternative to fitted bolts, rivets or preloaded high strength friction grip bolts (HSFG bolts). Load transfer may occur through shear and bearing (non-preloaded injection bolts) or through shear and bearing plus friction (preloaded injection bolts). In comparison with "normal" preloaded bolts, injection bolts cannot suffer from sudden slip in case of overload. In case of preloaded injection bolts, as load transfer is by friction and bearing, it is leading to a very strong stiff and very slip resistant connection.

Injection bolts can be manufactured from normal standard structural bolts. The bolts and washers are adapted to enable the injection of the resin. As compared to other mechanical fasteners, injection bolts have several advantages, which are listed below

- Behaviour of a fitted bolt, but much cheaper
- Solution for connections with a low slip factor
- Compact connections
- No slip in case of overload
- Good design resistance in bearing
- No special requirements for the contact surfaces
- No internal corrosion

Injection bolts also have some disadvantages, mainly including

- Preparation of the bolts and washers before assembly
- Preparation of the resin and injection of the cavity
- Good mechanical behaviour depending on weather conditions
- Not easy to dismantling after injection and curing of the resin

Injection bolts may be applied in new structures and in existing structures for repair and strengthening.

Figure 2.2: Injection bolts applied to repair an old heavily corroded riveted bridge Oranienburg (1994)

Design rules are given in the ECCS Recommendations (ECCS, 1994). These were the starting document for the sections on injection bolts in Eurocode 3 Part 1-8 (EN 1993-1-8, 2005). Rules for testing the resin and execution can be found in EN 1090-2 (EN 1090-2, 2008).

In last decades the use of injection bolts has increased, also for structures where the main load is only short duration such as for the new glass roof in the Amsterdam Central Railway station (Gresnigt and Beg, 2013), where short duration wind gusts are governing the design. In such applications higher bearing loads are acceptable, but to what level, and in which load combinations, etc.? To answer these and other questions that came up in recent decades, more research is needed to achieve economic and safe design rules.

2.1.4 Objectives of Task 3.2

Further development and optimization of connections with injection bolts to achieve slip and creep resistant bolted connections considering various influencing parameters.

The research will comprise short and long duration testing and fatigue testing to be performed at TU Delft. Non-preloaded injection and preloaded injection bolts are included.

Based on the results of the research guidelines for the design and installation of injection bolts will be setup, more in detail:

- Modification of test procedures for design bearing stresses in EN 1090-2, taking into account various loading conditions. Quality assurance of installation and quality assurance of applied resin.
- Design rules for EN 1993-1-8 for various geometries and loading conditions (static, shock, fatigue). Stiffness of connections with injection bolts; comparison with connections with “normal” preloaded bolts and with welded connections.
- Guidance and dissemination of knowledge on design, testing and installation, application examples.

2.2 Description of activities and discussion

2.2.1 Overviews of the experiment

2.2.1.1 Influencing parameters

There are so many influencing parameters that should be involved in the experiment. The main categories of influencing parameters include the type of the resin, the geometric and mechanical characteristics of the bolt, the curing condition of the resin, and the load type. Each category can be divided into several subclass and each subclass is including several typical parameters.

The main influencing parameters considered at the experiments of Task 3.2 are listed in table 2.1 below.

Table 2.1: Influencing parameters of the experiments of Task 3.2

Category	Subclass	Parameter
Resin	Initial	Araldite SW404 + HY2404
	Alternative	Edilon Dex-R2K / Edilon Dex-G20 Sikadur 30 / Sika injection 451
Bolt	Type	Non-preloaded injection
	Size	M20 / M36
	Hole and clearance	Normal round hole with 2mm / 3mm Slotted hole with 4mm / 6mm
	Thickness of plate stack	40mm / 80mm / 100mm
Curing	Time	6 hours / 24 hours / 48 hours / 72 hours
	Temperature	8˚C / 16˚C / 24˚C / Ambient temperature
Load	Static	Short duration / Long duration
	Dynamic	Fatigue

For all the experiments of Task 3.2, one steel grade is proposed: S355, and one bolt grade is proposed: 10.9.

2.2.1.2 Experimental stages and test numbers

In order to achieve the research objectives described in 2.1.4, a well thought-out experimental plan must be developed. Due to there are so many influencing parameters, so the whole experiment should be divided into several test stages, some of stages could be subdivided into several test steps again, in each of stages or steps only few of influencing parameters are concerned.

The experimental stages and test numbers of Task 3.2 are listed in table 2.2 below.

Table 2.2: Experimental stages and test numbers of Task 3.2

Stage	Step	Test number	
		Initial test	Supplementary
Stage 1: Short term test	Step 1: Resin injection	5	
	Step 2: Resin curing temperature	12	14
	Step 3: Resin loading delay	12	
Stage 2: Long term test		16	8
Stage 3: Fatigue test		8	
Stage 4: Large bolts test		4	
Stage 5: Long bolts test		8	
Total		**87**	

2.2.2 Short term test (Stage 1)

At stage 1, all of the bolts size are M20, using normal round hole with 2 mm clearance, only non-preloaded bolt is considered. The load type is short term, loading time varying from about 10 minutes to several days. Stage 1 has been divided into 3 steps, each step focus on the different testing objectives and emphasize on different influencing parameters.

2.2.2.1 Testing of resin injection (Step 1)

2.2.2.1.1 Objectives

Various resins have been selected as candidates for use in injection bolts to examine the feasibility and effectiveness of the injection.

The initial resin recommended in ECCS is

- Araldite

The alternative resin are

- Edilon Dex-R2K
- Edilon Dex-G20
- Sikadur 30
- Sika injection 451

Araldite is the initial resin recommended in ECCS(1994), which is a two components resin, the SW404 is the primer and the HY2404 is the hardener.

Four new kinds of resin have been selected to find which one could be as the alternative resin for Araldite.

2.2.2.1.2 Experimental plan

For each kinds of resin mentioned above, only one specimen has been injected and tested. The main influencing parameters are listed in Table 2.3.

Table 2.3: Specimen details of Stage 1 - Step 1

Bolt type	Bolt size	Hole & Clearance	Resin type	Curing temperature	Curing time (hours)	Number of specimens
Non-preloaded	M20 ×80 mm	Round 2mm	Araldite	Ambient temperature (about 24 ℃)	72	1
			Edilon Dex-R2K			1
			Edilon Dex-G20			1
			Sikadur 30			1
			Sika injection 451			1
Total						**5**

Note: All the specimens listed in the table above have already been tested at July, 2016. Because the testing was carried in the summer time, the curing temperature, which was listed in the table as '*the ambient temperature*', was approximately 24 °C.

2.2.2.1.3 Dimension of specimen

According to EN 1090-2, a standard specimen with M20 bolt has been adopted. This test specimen has a top and bottom connection of two injection bolts at per connection. The bolt size is M20×80 mm. The bolt is placed in a normal round hole of 22 mm, that is to say the maximum clearance existed between the hole and the bolt shank is 2 mm. This kind of specimen has been used in all of the other steps of stage 1.

The dimension of the specimen is shown in Figure 2.3 below.

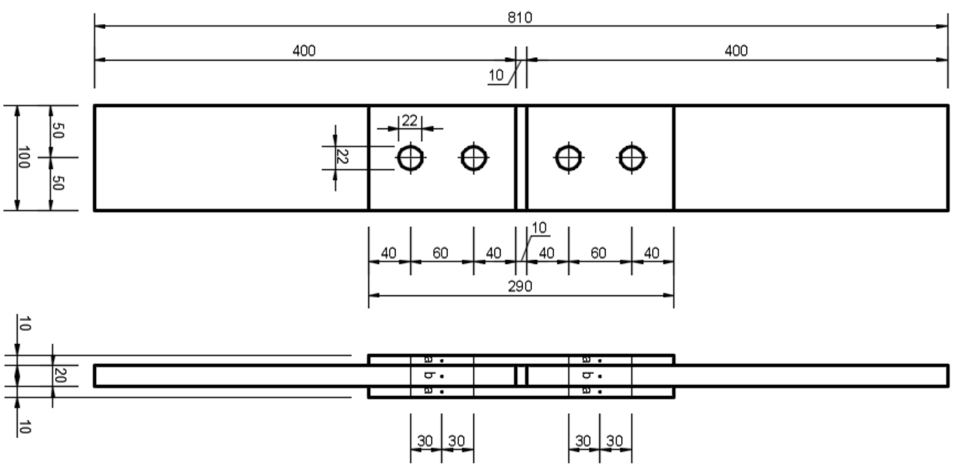


Figure 2.3: Dimension of specimen of stage 1

2.2.2.1.4 Specimen assembly

According to the geometry in Figure 2.3, specimens have been assembly firstly. To prevent resin from spreading in between the plate surfaces of the connection the bolts are tightened to 80 Nm, during assembly of the test specimens the center plates are pushed together. This ensures the maximum resin layer of 2 mm is on the compressed side. This is the “worst case” scenario for the play in the bolt hole.

In Stage 1, old plates in Task 2.1 of Siroco which had been already performed also in TU Delft were used again. But the bolts, nuts and washers were new components.

2.2.2.1.5 Resin injection and curing

The injection and curing of all test specimens was done at ambient temperature in the Stevin Laboratory, that was approximately 25 °C. Furthermore the injection was carried out with a hand operated injection pistol. The resin was injected until resin visibly flowed out of the washer on the opposite side of the connection.

The injection pistol with a set of equipment including a plastic cylinder, a nozzle and a lid are shown in Figure 2.4, also with a bottle of resin, the Araldite, SW404 and the hardener HY2404. This pistol and the equipment was also used for injecting the resin Edilon Dex-G20, the Sikadur 30 and the Sika injection 451. So the two components of these resins must be premixed before put it in the plastic cylinder and perform injection.

Figure 2.4: Injection pistol and equipment with resin Araldite

But for resin Edilon Dex-R2K, a special injection pistol was used, which is shown in Figure 2.5. Because the resin bottle is a conjoined twin cylinder, so the mixing process is automatic during the injection procedure. The advantage is that no premixing is required for Dex-R2K compared with the other resins, but this may bring the disadvantage of non-uniform mixing, which we will discuss later.

Figure 2.5: Special injection pistol only used for resin Edilon Dex-R2K

After the specimens have been injected they were left to cure at room temperature for at least 72 hours.

2.2.2.1.6 Measurement setup

During the test displacements in the top and bottom connections were measured using 12 LVDT's. We measure for both connections the relative displacement between the center plate and the cover plates at the plate edge. Furthermore we measure the relative displacement between center plate and cover plates at the heart of the bolt group of the connections. The LVDT's measurement range is 2 mm and the accuracy is 0.001 mm. The serial number and location of the 12 LVDT's in a specimen is shown in Figure 2.6 below.

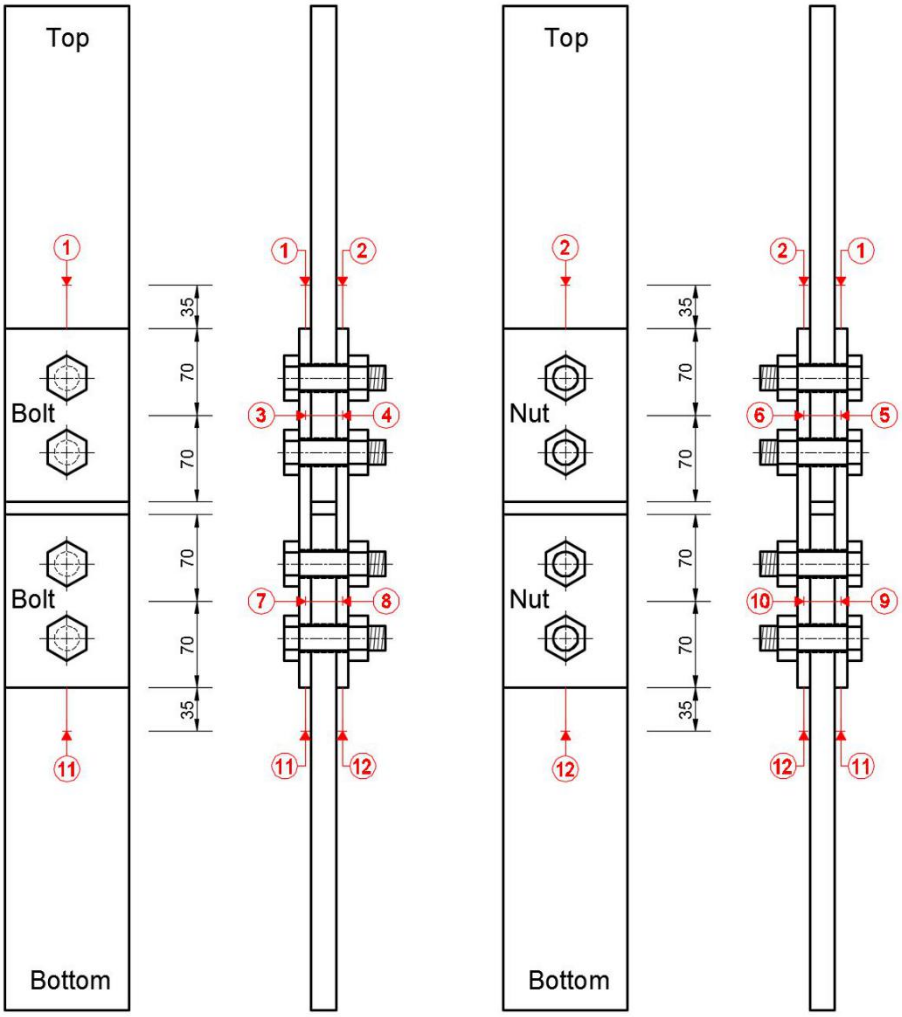


Figure 2.6: Serial number and location of 12 LVDT's in a specimen

2.2.2.1.7 Test procedure

Following the guidelines as specified in EN-1090 appendix K we determine for all test specimens the tensile force needed to achieve a displacement at the center of the bolt group of 0.15 mm. Testing is done in a short duration taking between 10 and 15 minutes. This test is performed using a force controlled procedure with a ramp rate of 0.3 kN/s. The temperature during testing is once again room temperature of the Stevin Laboratory.

After we have reached the slip 0.15 mm we then proceed to reverse the loading to a small compressive force of 25 kN for all specimens. This is to get an indication of the deformation of the resin on the non -compressed side. Finally as specified in the EN-1090 appendix K we once again apply a tensile load on the specimen equal to 90% of the value found for a slip of 0.15 mm. After this we keep the load on the specimen constant for a few hours to get an initial idea of the time dependent behaviour of the resin.

Because before injection, a torque equals to 80 Nm had been applied in the nuts to ensure the resin would not permeate between the plates. When the curing time had been finished, in order to prevent friction between the plates playing a role in loading, the nuts are loosened and then hand tightened to remove any preload in the bolts.

For emphasize, some key points of test procedure in stage 1- step 1 can be concluded below

- Force controlled with a ramp of 0.3 kN/s
- Load to the force when the displacements on both connections reach to 0.15 mm
- Reverse load to compressive force equal to 25 kN
- Load again to 90% of the value for slip equal to 0.15mm and keep it at least 5 hours
- 80 Nm torque applied in all of the nuts before injection and replaced by hand tightening after curing

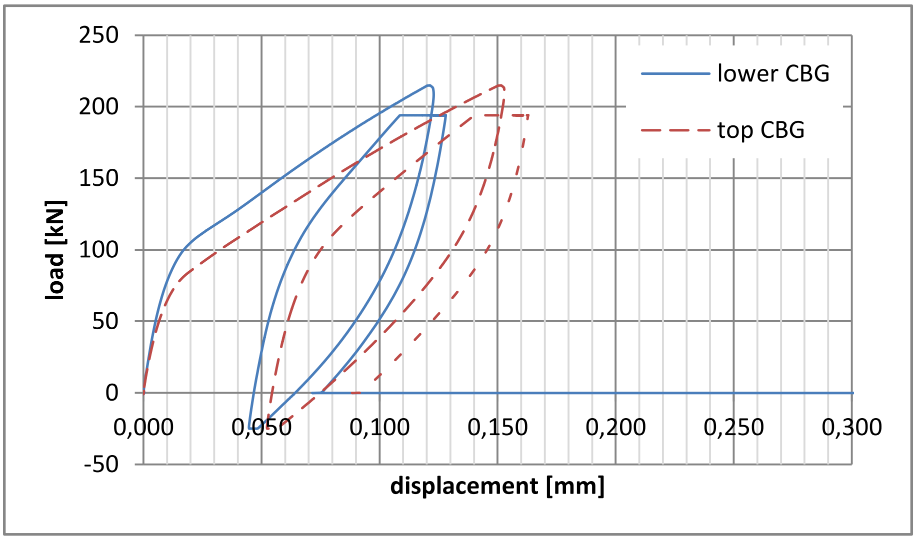
The maximum tension capacity of the test machine is 500 kN. One of the specimens was loading in the testing machine is shown in Figure 2.7 below.

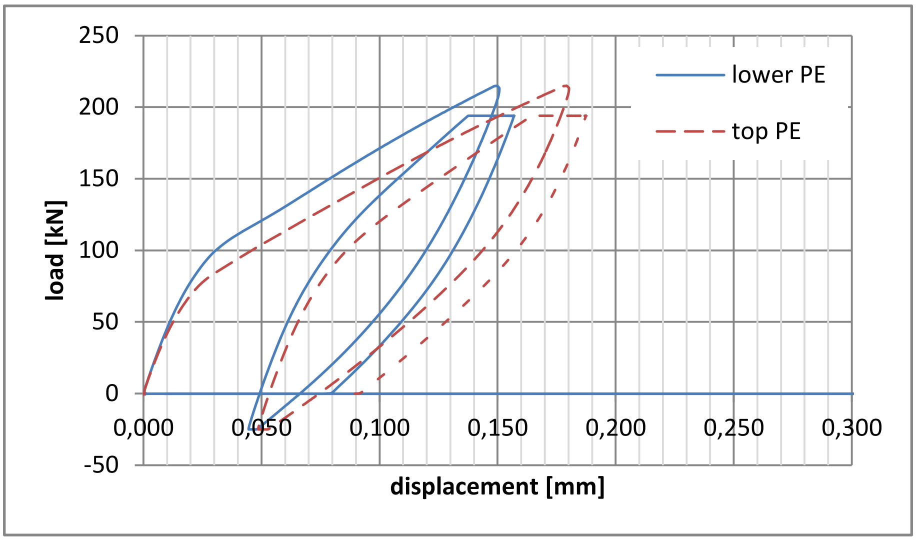
Figure 2.7: A specimen loading in the testing machine with 12 LVDT's

2.2.2.1.8 Test results

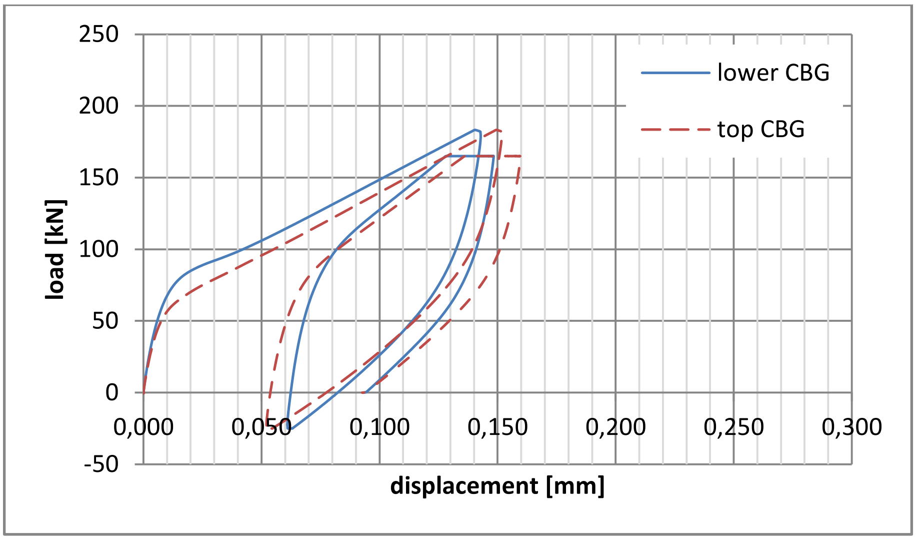
According to the test procedure listed above, five specimens for each kinds of resin had been tested at July, 2016. Out of the five resin the Sika injection 451 resin test results were not usable. Due to the low viscosity, this resin penetrated the cavity between the plates of the test specimen. This lead to a glued connection between the plates which failed abruptly. For this reason Sika injection 451 is left out of the following analysis of test results.

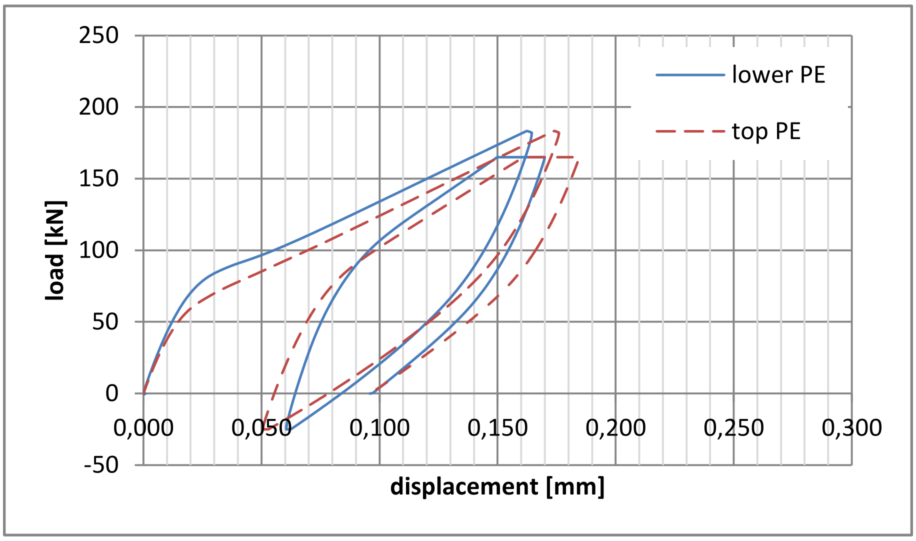
First of all, the load-displacement curves of four resins are shown in Figure 2.8. For each of the resins, two graphs are drawn, one is the load-displacement curves at the center of the bolt group (CBG), the other is the load-displacement curves at the plate edge (PE). Due to including more elastic deformation of the plates, the displacements at PE are great than the displacements at CBG at the same force value, that is to say, for the same slip value, the forces at PE are less than the forces at CBG.



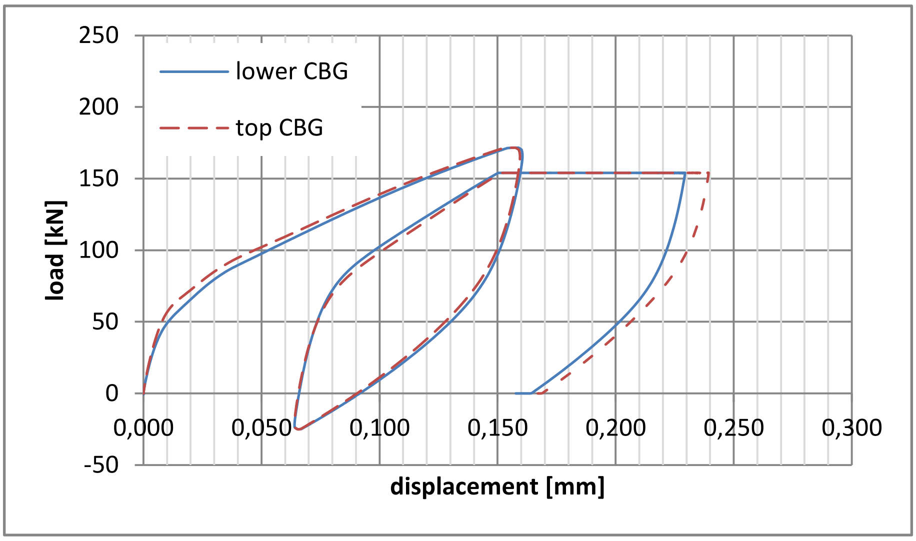


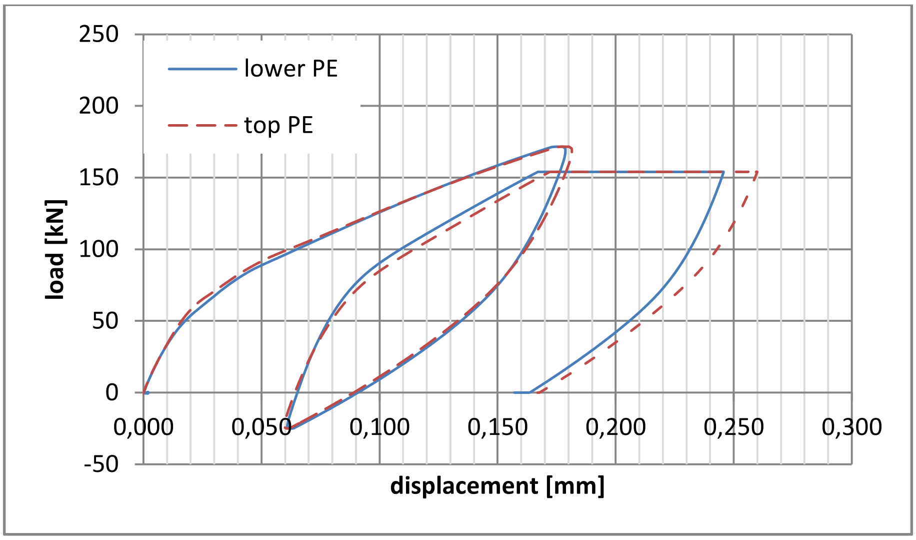
(a) Araldite



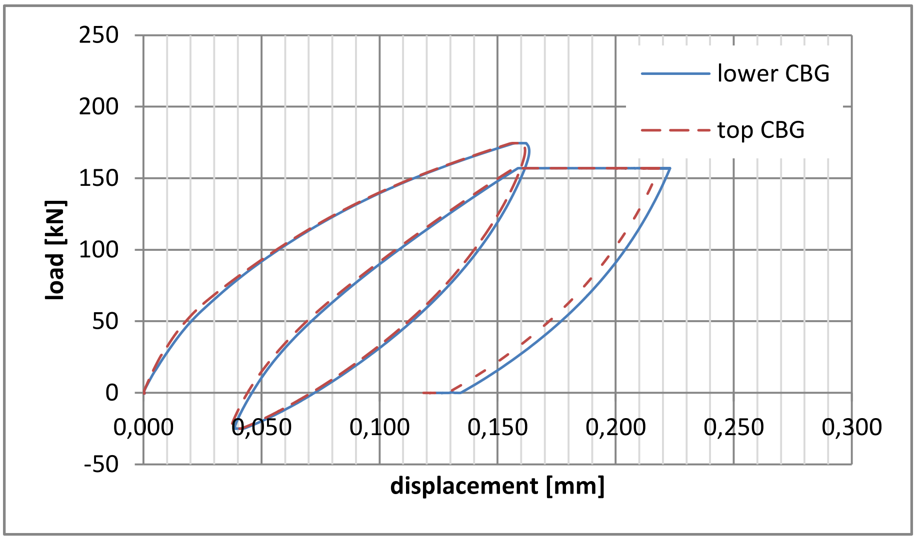


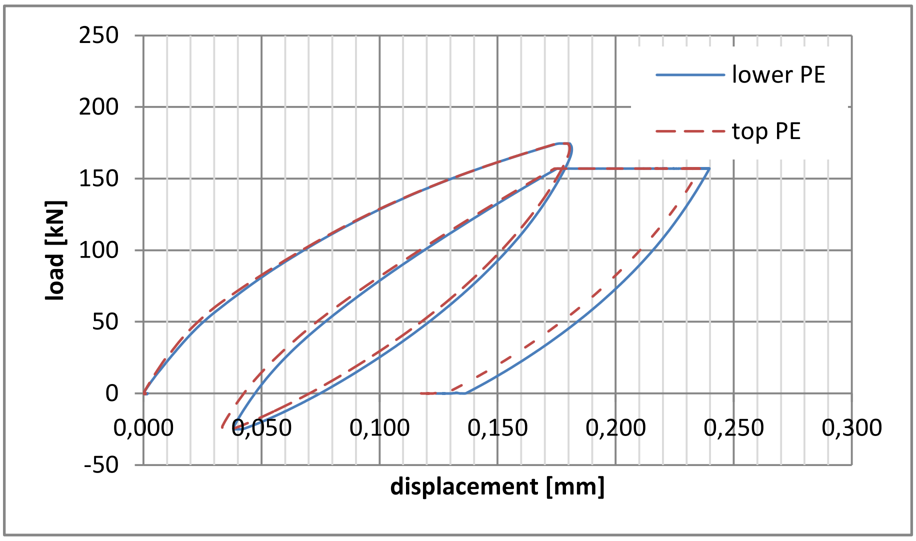
(b) Edilon Dex-R2K





(c) Edilon Dex-G20

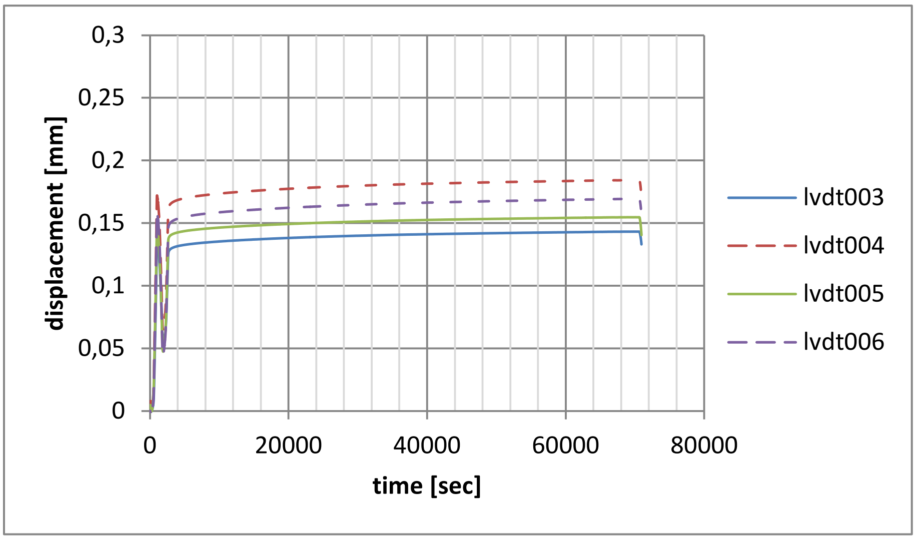


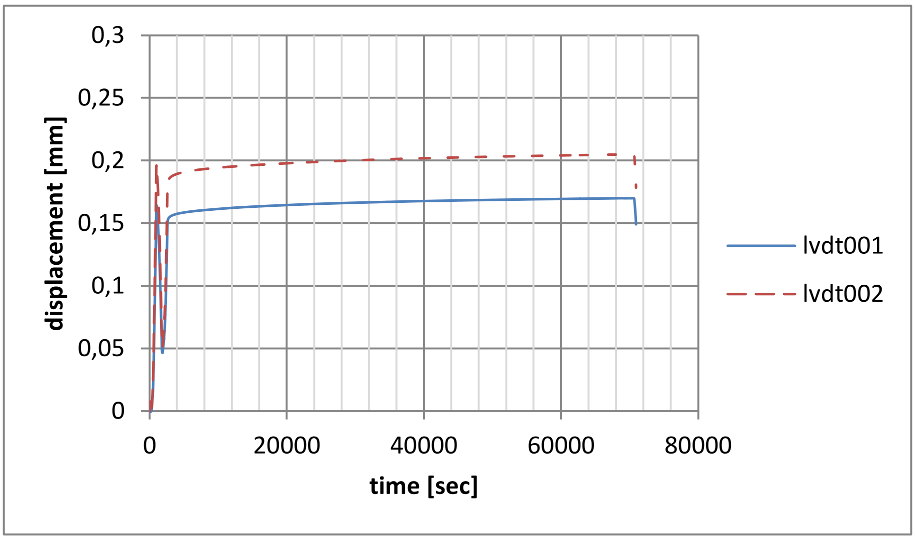


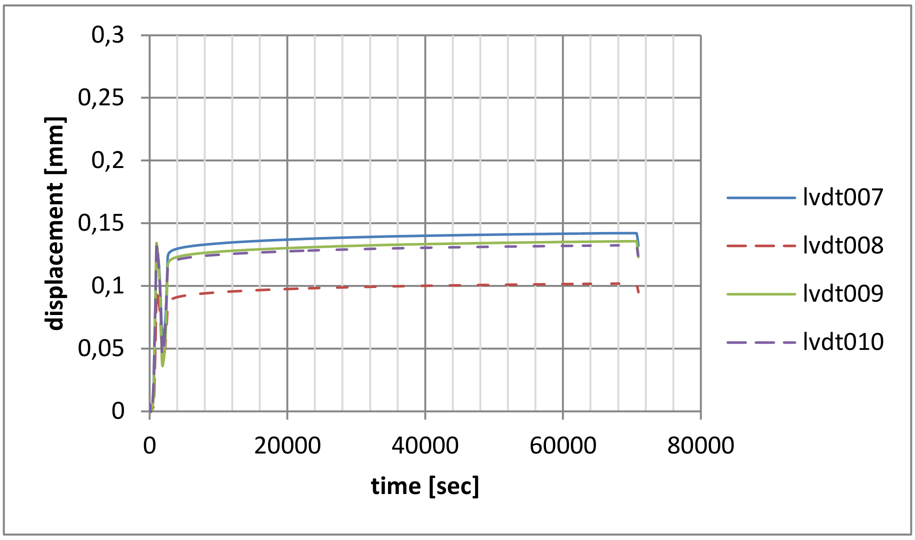
(d) Sikadur 30

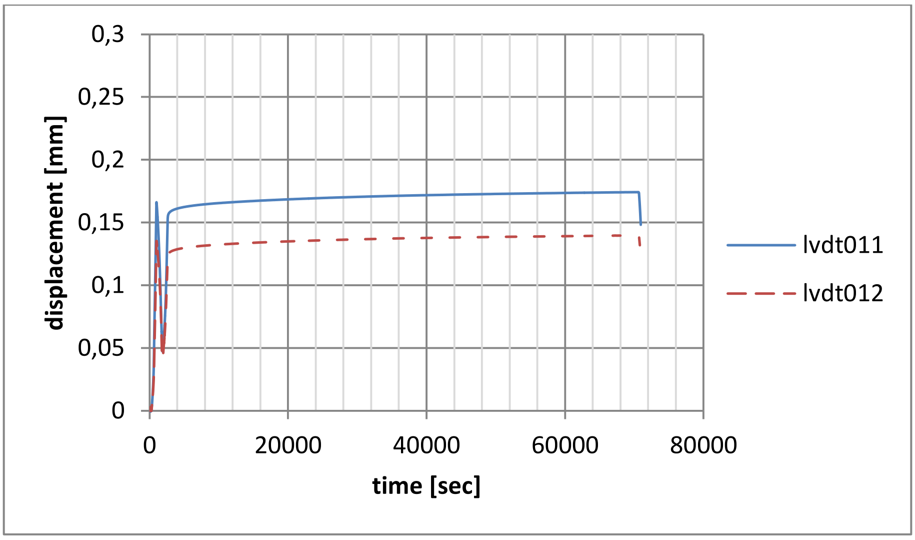
Figure 2.8: Load vs displacement curves of four resins of Stage 1 - Step 1

Secondly, the displacement-time curves of these four resins are shown in Figure 2.9. According to the test procedure, the force was reloaded to 90% of the value for slip equal to 0.15mm and keep it at least 5 hours. All of the 12 LVDT's location can be found in Figure 2.6.





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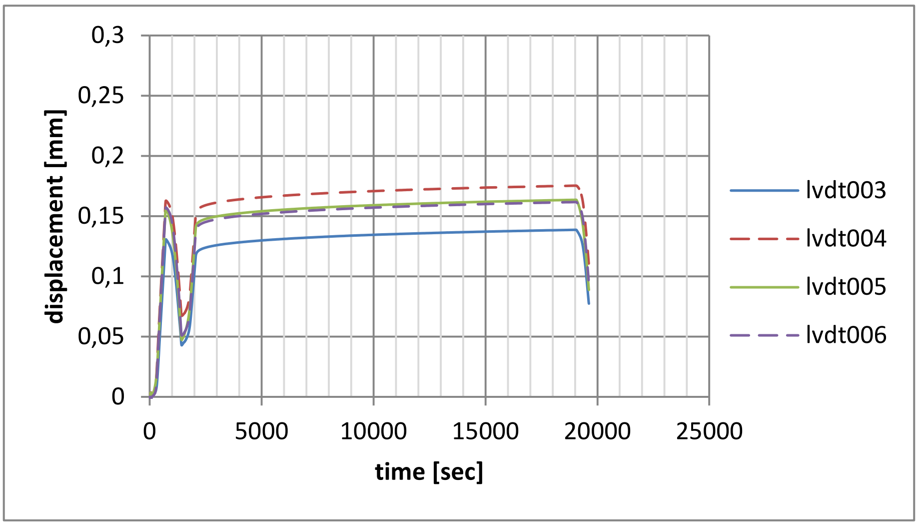
(a) Araldite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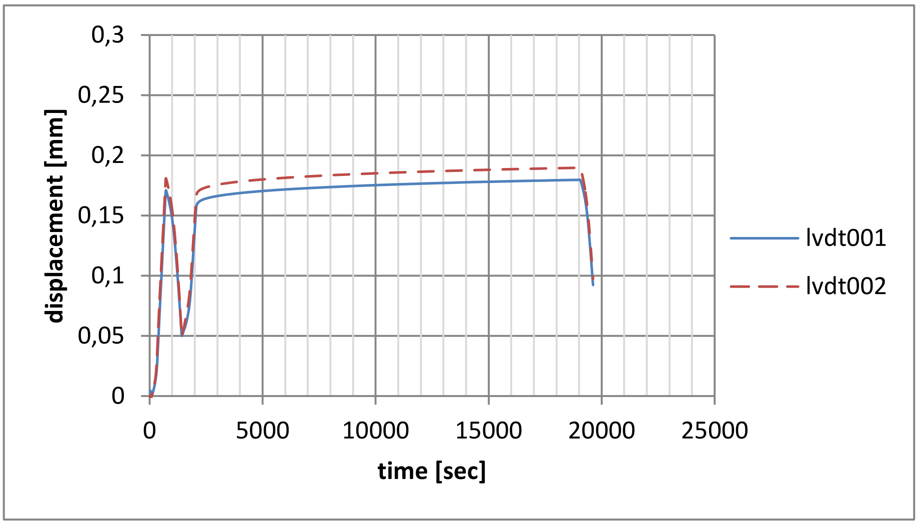
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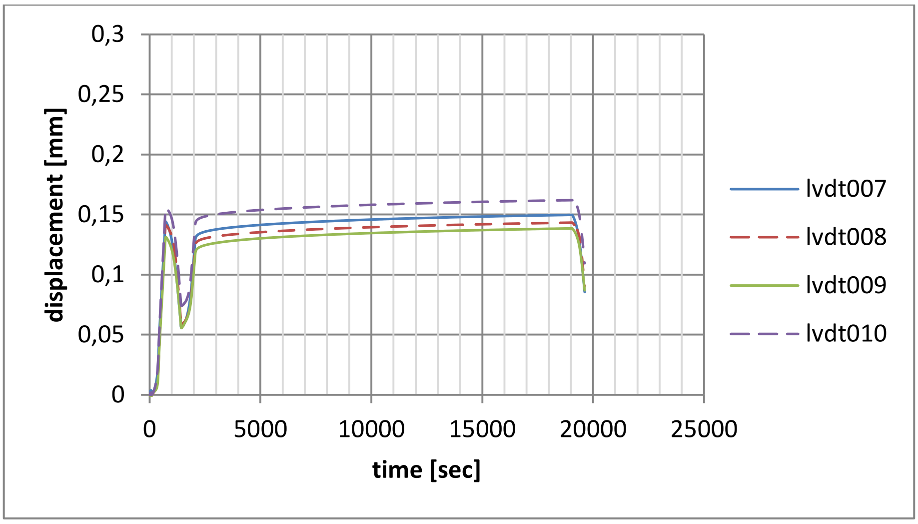
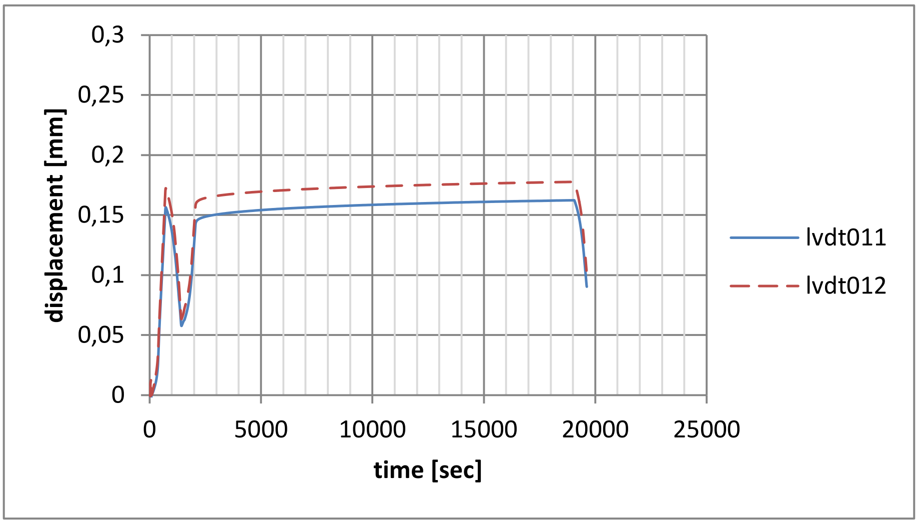
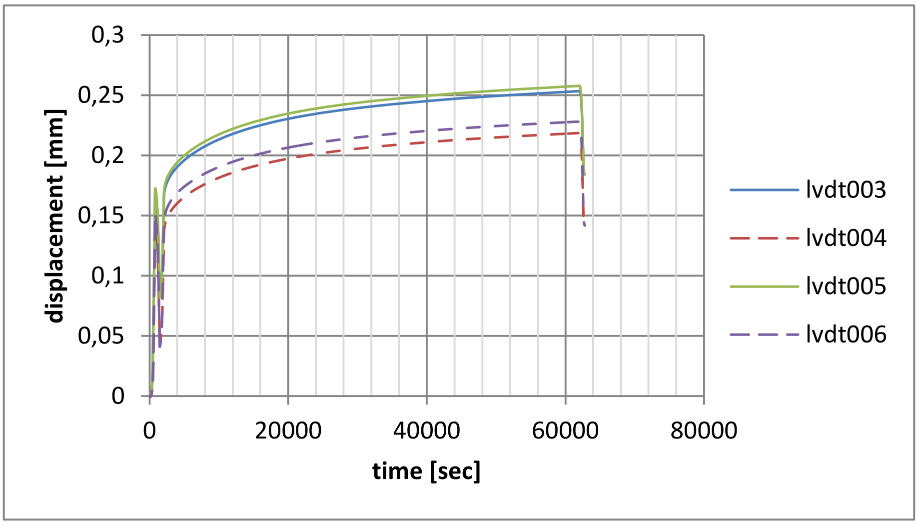
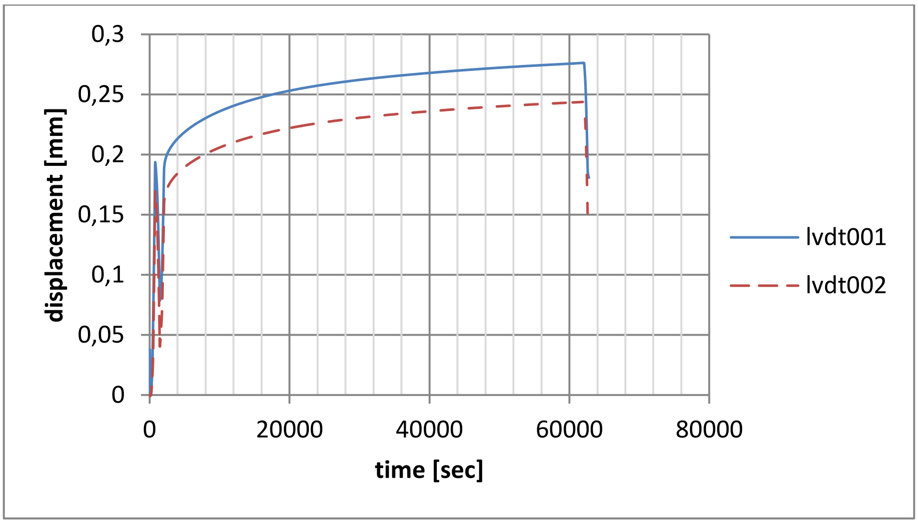
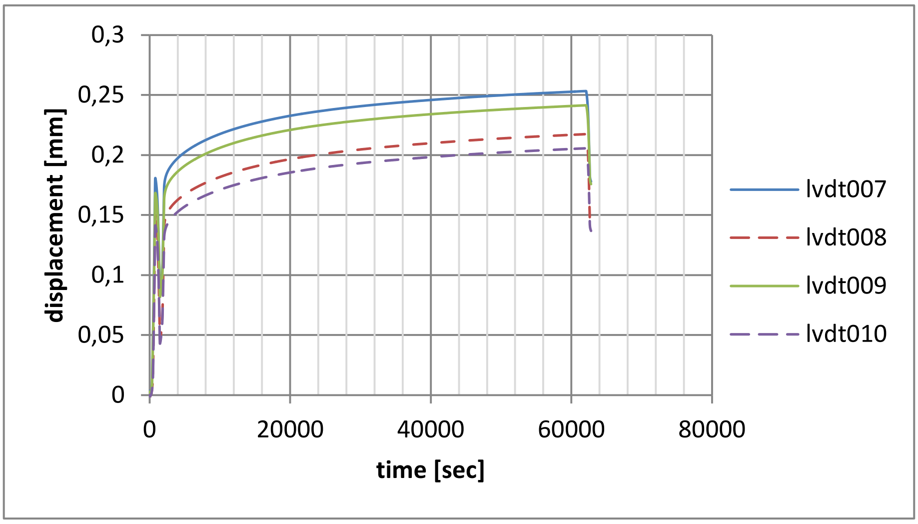


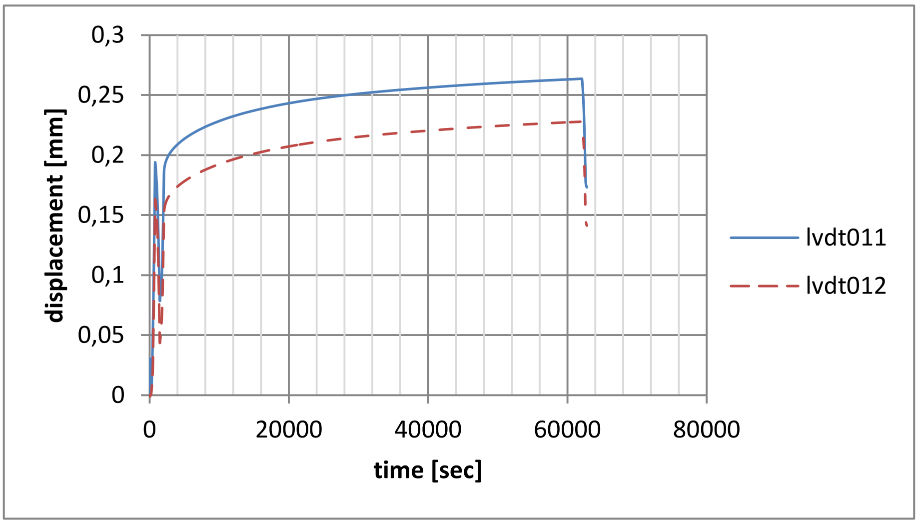


(b) Edilon Dex-R2K

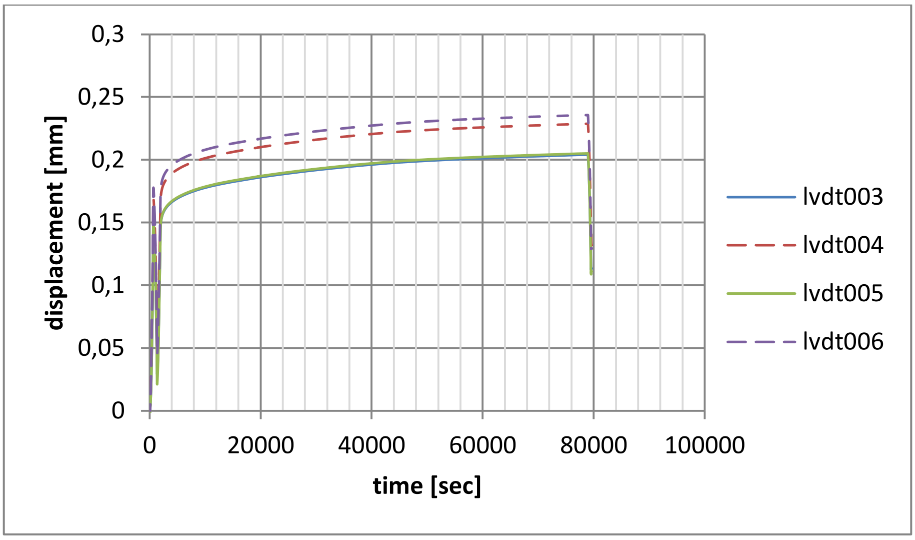








(c) Edilon Dex-G20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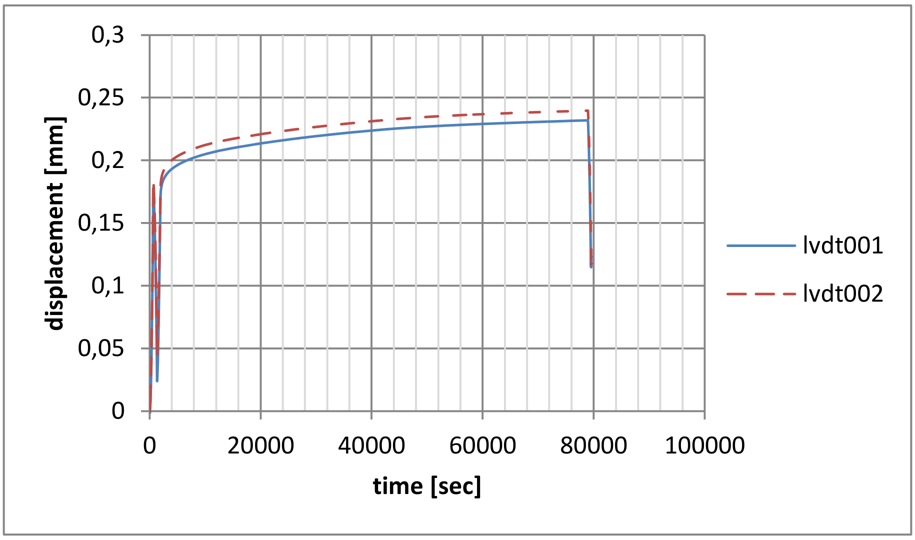
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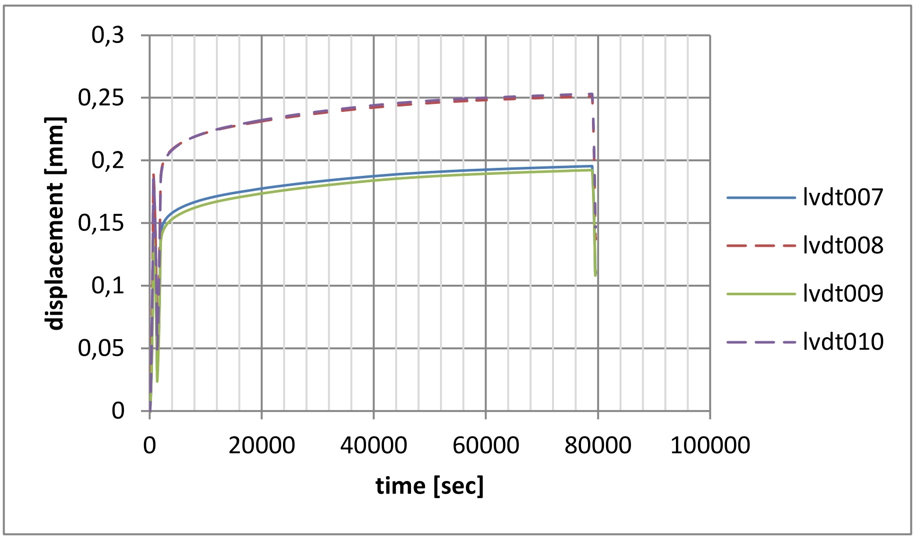
lvdt002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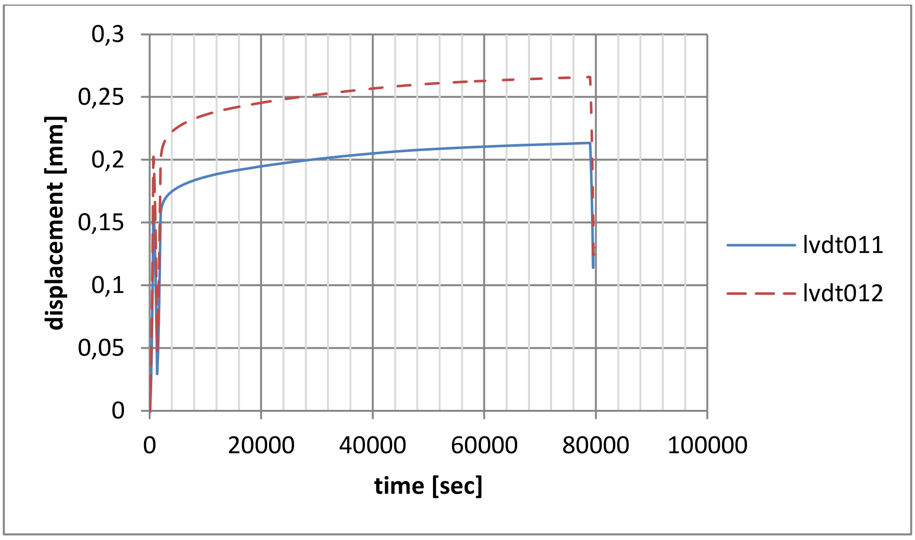
0,05
0
displacement [mm]
0
20000
40000
60000
80000
100000
time [sec]
lvdt007
lvdt008
lvdt009
lvdt010



(d) Sikadur 30

Figure 2.9: Displacement vs time curves of four resins of Stage 1 - Step 1

2.2.2.1.9 Analyses

Based on the load-displacement curves in Figure 2.8, the tensile force that was applied to reach a slip value of 0.15 mm at the center of the bolt group (CBG) and at the plate edge (PE) are listed in Table 2.4. The ratio of force for 0.15 mm at PE and at CBG are also listed in this Table.

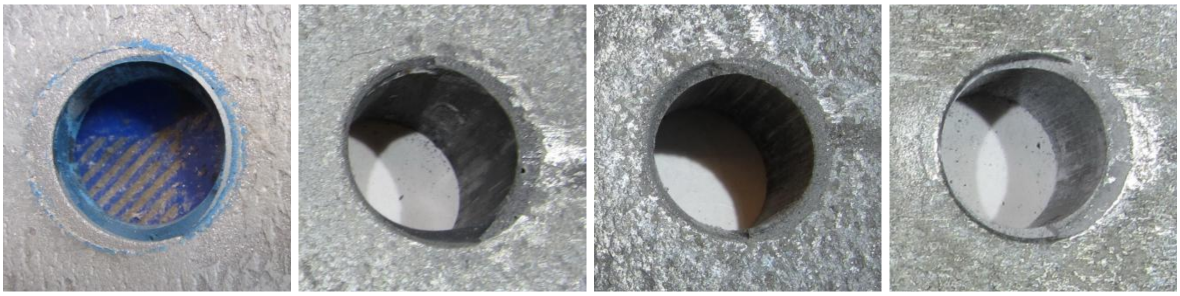
Table 2.4: Tensile force value at the slip value of 0.15 mm of Stage 1 - Step 1

Resin type	Force for 0.15mm at CBG (kN)			Force for 0.15mm at PE (kN)			Ratio of average force at PE/CBG
	Top	Lower	Average	Top	Lower	Average	
Araldite	214	215	**214.5**	193	215	204.0	0.951
Edilon Dex-R2K	183	183	**183.0**	164	173	168.5	0.921
Edilon Dex-G20	170	169	**169.5**	157	158	157.5	0.929
Sikadur 30	171	171	**171.0**	161	161	161.0	0.942

By comparing the displacement-time curves in Figure 2.9, the resin Araldite shows the best time dependent behaviour and the resin Edilon Dex-R2K would take the second place. The other two resins, which are Edilon Dex-G20 and Sikadur 30, shows very large creep at this load level only in the first 5 hours loading.

2.2.2.1.10 Visual inspection of resin injection

After the tests, all the specimen have been dismantled to find a visual impression of the resin filling effect in the bolt hole. This was done by removing the bolts from the specimens by pressing them out with a hydraulic press. Afterwards the surfaces of the plates and the walls of the bolt holes have been inspected, the resin layer in the bolt hole have been shown in Figure 2.10.



(a) Araldite **(b) Edilon Dex-R2K** **(c) Edilon Dex-G20** **(d) Sikadur 30**

Figure 2.10: Resin layer in the bolt hole

Due to the large force required to dismantled the bolts, there is some damage to the resin layer. However from Figure 2.10, we can see that these four kinds of resins are filled very well in the cavities between the bolt shank and the hole wall of the plates.

From the visual inspection all the four kinds of resin showed a correct filling with no obvious gaps where the resin did not flow. What furthermore was observed with these resins was a correct positioning of the bolt in the bolt hole. A small area on the side of the hole did not have any resin, this was the location where the bolt shaft touched the steel plate due to them being pushed together during assembly. This can be seen in the images that have been added.

Another visual inspection can be obtained by a cutting section from the specimen injected with resin Araldite, which is shown in Figure 2.11. We can see from it to get the same conclusion mentioned above.

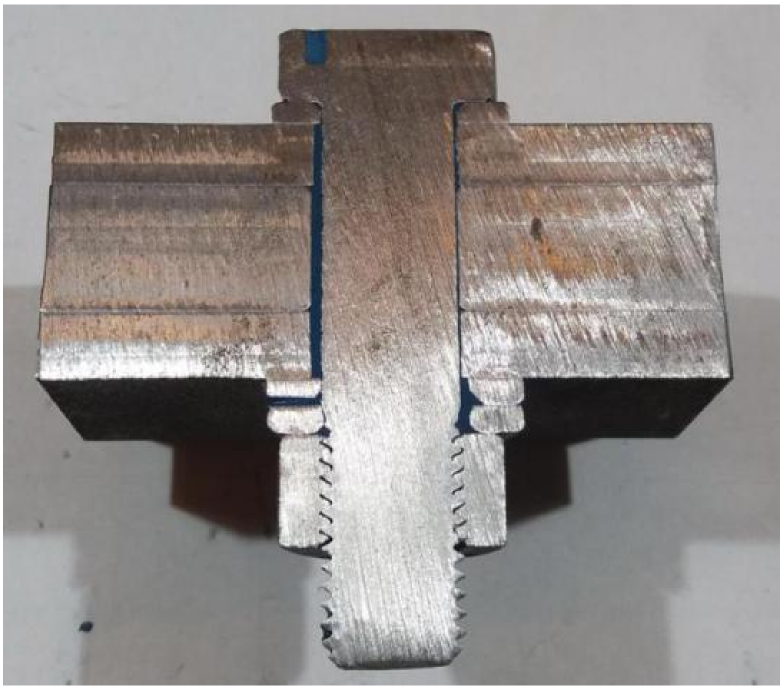


Figure 2.11: A cutting section from the specimen injected with Araldite

But for the fifth resin, Sika injection 451, we have already indicated that due to the low viscosity, this resin penetrated the cavity between the plate surfaces of the specimen. From Figure 2.12 below it is clear to see that this kind of resin penetrated between the plates to create a glue like bond. With the other tests resins there was no flow of resin between the plate surfaces could be observed.

Figure 2.12: An inner plate from the specimen injected with Sika injection 451

2.2.2.1.11 Conclusions

The main conclusion getting from this step can be listed below

- Araldite, the initial resin recommended in ECCS(1994), has achieved the highest tensile force value at the slip value of 0.15 mm, that is 214.5 kN at the center of the bolt group (CBG), and it has also shown the best time dependent behaviour in all of the test resins.
- Except Sika injection 451, three other selected resins for alternative, which are Edilon Dex-R2K, Edilon Dex-G20, and Sikadur 30 separately, all show up a good performance on resin injection.
- Edilon Dex-R2K has taken the second place behind Araldite, for this resin the tensile force value at the slip value of 0.15 mm is 183.0 kN at CBG, and its creep behaviour is not so large as well.
- For Edilon Dex-G20, the tensile force value at the slip value of 0.15 mm is 169.5 kN at CBG, and for Sikadur 30, the same type of force value is 171.0 kN, but both of them have a significant creep behaviour.
- Sika injection 451 has not obtained usable results at all and will not be considered in the following researches.

2.2.2.2 Testing of resin curing temperature (Step 2)

2.2.2.2.1 Objectives

To research the strength and stiffness properties of 4 kinds of resins selected from step 1, varying the resin curing temperature on condition of keeping the same resin curing time.

Three curing temperatures are adopted, they are

The same curing time is

- 48 hours

Step 2 is a very important phase to find out the mechanical properties of different resins under different curing temperatures bearing short duration load. Based on the results of step 2, the bearing capacity of the resins, would be as the benchmark value using in the following researches.

2.2.2.2.2 Experimental plan

As an initial experimental plan, 12 specimens would be tested, in which 3 curing temperatures were selected. The main influencing parameters are listed in Table 2.5.

Table 2.5: Specimen details of Stage 1 - Step 2 (Initial test)

Bolt type	Bolt size	Hole & Clearance	Resin type	Curing temperature	Curing time (hours)	Number of specimens
Non-preloaded	M20 ×80 mm	Round 2mm	Araldite	8 °C	48	1
				16 °C		1
				24 °C		1
			Edilon Dex-R2K	8 °C		1
				16 °C		1
				24 °C		1
			Edilon Dex-G20	8 °C		1
				16 °C		1
				24 °C		1
			Sikadur 30	8 °C		1
				16 °C		1
				24 °C		1
Total						**12**

Note: All the specimens listed in the table above have already been tested at August, 2016.

After these 12 testing had been done, two kinds of resin, Araldite and Edilon Dex-R2K, were selected to carry on supplemental testing. In total 14 additional specimens have been tested as four batches. During these testing some test procedure has been changed and it will be introduced minutely at the following sections.

The main influencing parameters of these supplemental testing are listed in Table 2.6.

Table 2.6: Specimen details of Stage 1 - Step 2 (Supplementary)

Bolt type	Bolt size	Hole & Clearance	Resin type	Curing temperature	Curing time (hours)	Number of specimens			
						1st	2nd	3rd	4th
Non-preloaded	M20 ×80 mm	Round 2mm	Araldite	8 °C	48		2		
				16 °C		1			
				24 °C					
			Edilon Dex-R2K	8 °C			2		2
				16 °C		1		4	
				24 °C					2
Total						**14**			

Note: All the specimens listed in the table above have already been tested at September, 2016.

2.2.2.2.3 Dimension of specimen and measurement setup

The dimension of specimens is as same as the specimens testing in stage 1 - step 1, see Figure 2.3. Therefore the measurement setup is also as same as the measurement setup using in stage 1 - step 1, see Figure 2.6.

2.2.2.2.4 Test procedure

(1) Initial test

Firstly, specimens have been assembled according to the same criteria used in Step 1, but one operation have been changed that the torque value, which was 100 Nm instead of 80 Nm to make sure of the surfaces of the plates contacted well before the resin injecting.

In order to examine the temperature dependency of the curing of the resin the test specimens have been placed in a refrigerator at the require temperature for 4 days prior to the injection procedure. The resin itself was kept at 20 °C in a climate controlled room.

The specimens were taken out of the refrigerator, the injection was performed and the specimens have been then placed back to let them cure at the specified temperature for 48 hours before testing was performed. In order to limit heating of the specimens after they had been taken out of the refrigerator using bubble plastic to insulate them with the higher temperature air. The temperatures at which the curing had been done were 8 °C, 16 °C and 24 °C, as shown in Table 2.5.

Tests in Step 2 was also a short term duration test like tests in Step 1. But the force control speed had been changed to 0.2kN/s instead of 0.3kN/m, and only monotonic loading to the force when the slip reach to 0.20 mm, then unload to zero to finish the test.

For emphasize, some key points of test procedure in stage 1- step 2 can be concluded below

- Force controlled with a ramp of 0.2 kN/s
- Load to the force when the displacements on both connections reach to 0.20 mm
- Unload immediately to 0 kN and loading finished
- 100 Nm torque applied in all of the nuts before injection and replaced by hand tightening after curing

The refrigerator used in this phrase is shown in Figure 2.13.

Figure 2.13: The refrigerator in Stevin Laboratory of TU Delft

(2) Supplementary

Almost the same test procedure have been used in supplementary testing of Step 2. For the sake of simplicity, only the key points of test procedure are described below for the four batches separately.

I. The 1st batch

Two supplementary specimens have been tested in this batch, one was Araldite and another was Edilon Dex-R2K, the curing temperature was 16 °C.

Key points of test procedure are

- Force controlled with a ramp of 0.2 kN/s
- Load to the force when the displacements on both connections reach to 0.20 mm
- Increasing the force ramp to 1.0 kN/s, continue loading until reach to 500 kN, which is the maximum tensile capacity of the test machine
- Unload immediately to 0 kN and loading finished
- 100 Nm torque applied in all of the nuts before injection and replaced by hand tightening after curing

II. The 2nd batch

Four supplementary specimens have been tested in this batch, two specimens were Araldite and the others were Edilon Dex-R2K, the curing temperature was 8 °C.

We have already mentioned before, it is the old plates in Task 2.1 of Siroco project were used again in all the specimens of Stage 1. Before this batch's test, the old plates we used has a very high friction coefficient at the surface, the coefficient is about 0.8 and the name of the coating is *ASI-Zn*. Because it maybe cause some degree of friction force between the plates and maybe increase the bearing capacity of the connection, even in the condition of non-preloaded injection bolts. So we decided to use another kind of old plates for comparison, which is the *B-series* plates, and it has a low friction coefficient about 0.25.

So in this batch of test, for each of resin, two specimens have been assembled with the high friction coefficient surface plates, two specimens have been assembled with the low friction coefficient surface plates.

Key points of test procedure are

- Force controlled with a ramp of 0.2 kN/s
- Load to the force when the displacements on both connections reach to 0.20 mm
- Increasing the force ramp to 1.0 kN/s, continue loading until reach to 500 kN
- For the first 3 specimens, unload immediately to 0 kN and loading finished
- For the 4th specimen, keeping 500kN for 16 hours then unload to 0 kN, in this specimen the resin is Edilon Dex-R2K, the plated surface is *B-series*
- 100 Nm torque applied in all of the nuts before injection and replaced by hand tightening after curing

III. The 3rd batch

Four supplementary specimens have been tested in this batch, all of them were Edilon Dex-R2K, the curing temperature was 16 °C.

In order to reduce the effects of the friction between plates furthest, 30 Nm torque has been used for pre-tightening instead of 100 Nm used before. Another change was the type of the plates, *B-series* plate surfaces has been used to assemble the specimens, which has a low friction coefficient only about 0.25.

This kind of plate and the value of 30 Nm torque would be used as the standard test procedure at the subsequent tests of Stage 1, that is the 4th batch of Step 2 and the Step 3.

Key points of test procedure are

- Force controlled with a ramp of 0.2 kN/s

- Load to the force when the displacements on both connections reach to 0.20 mm
- Increasing the force ramp to 1.0 kN/s, continue loading until reach to 500 kN
- Unload immediately to 0 kN and loading finished
- 30 Nm torque applied in all of the nuts before injection and replaced by hand tightening after curing

IV. The 4th batch

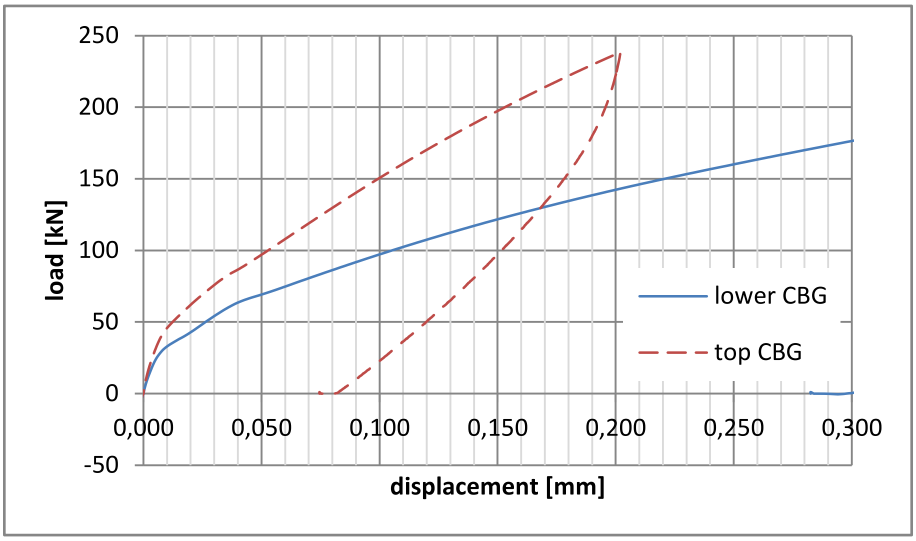
Four supplementary specimens have been tested in this batch, all of them were Edilon Dex-R2K, the curing temperature were 8 °C and 24 °C, for each temperature had two specimens.

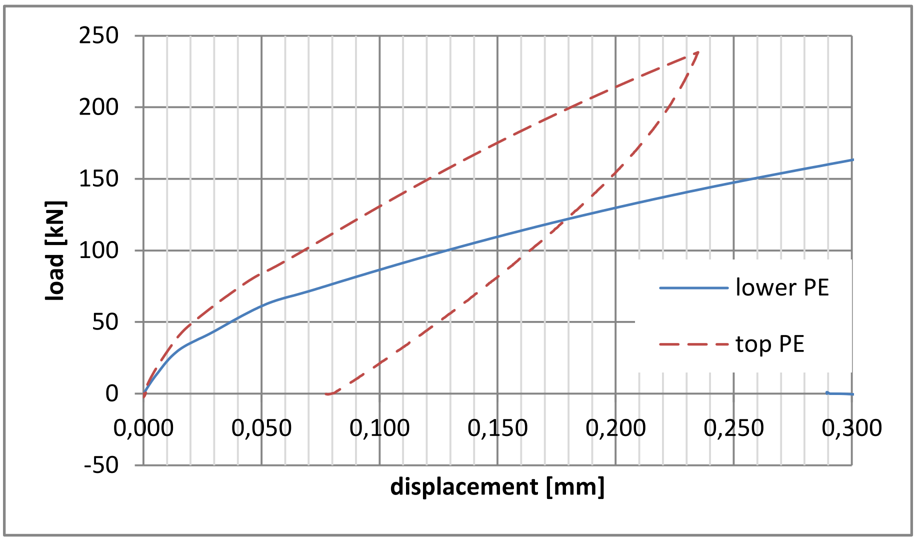
All the test procedure had not changed again and was as same as in the 3rd batch.

2.2.2.2.5 Test results and analyses

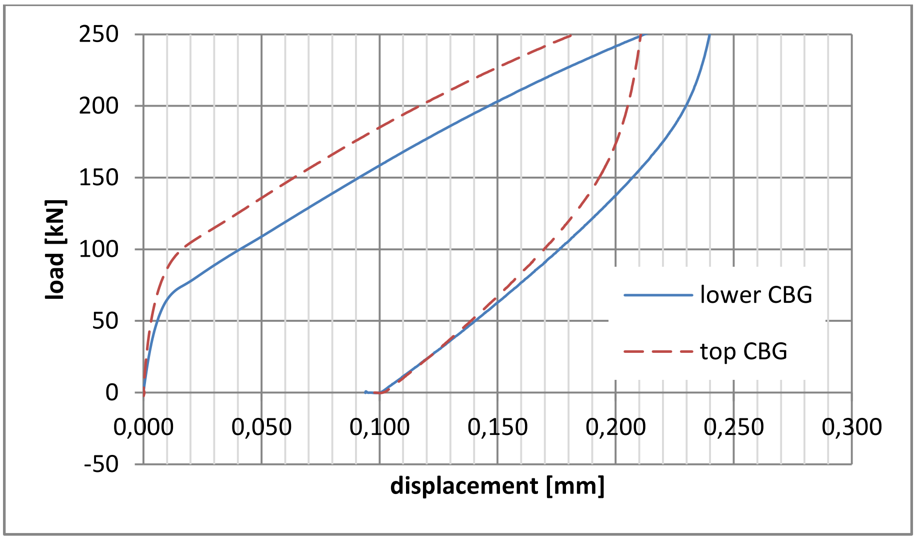
(1) Initial test

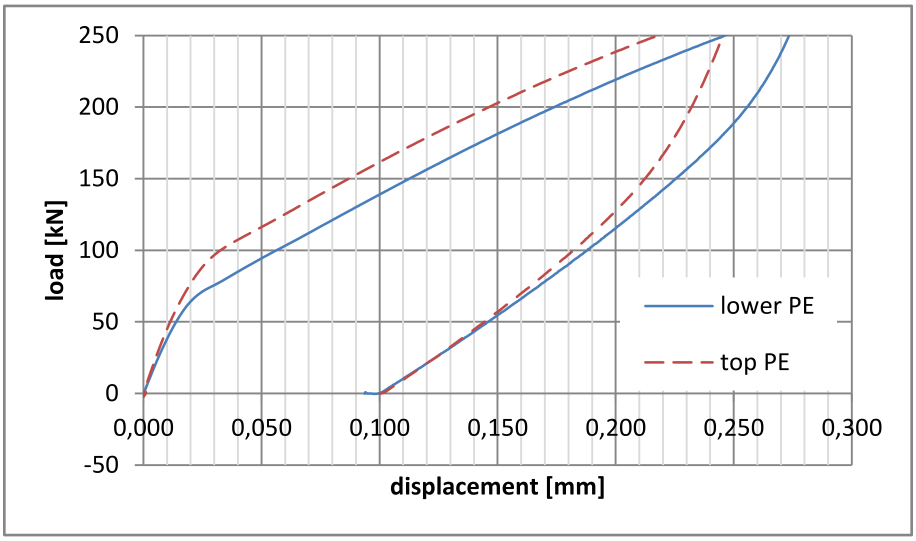
First of all, the load-displacement curves of four resins at three different curing temperatures are shown in Figure 2.14, except resin Sikadur 30 at 24 °C. For each of them, two graphs are drawn, the load-displacement curves at the center of the bolt group (CBG) and at the plate edge (PE).



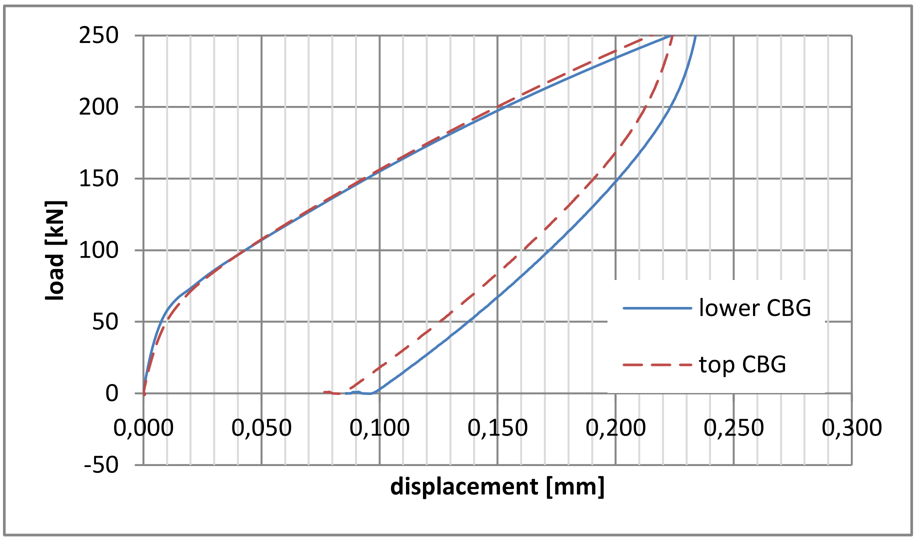


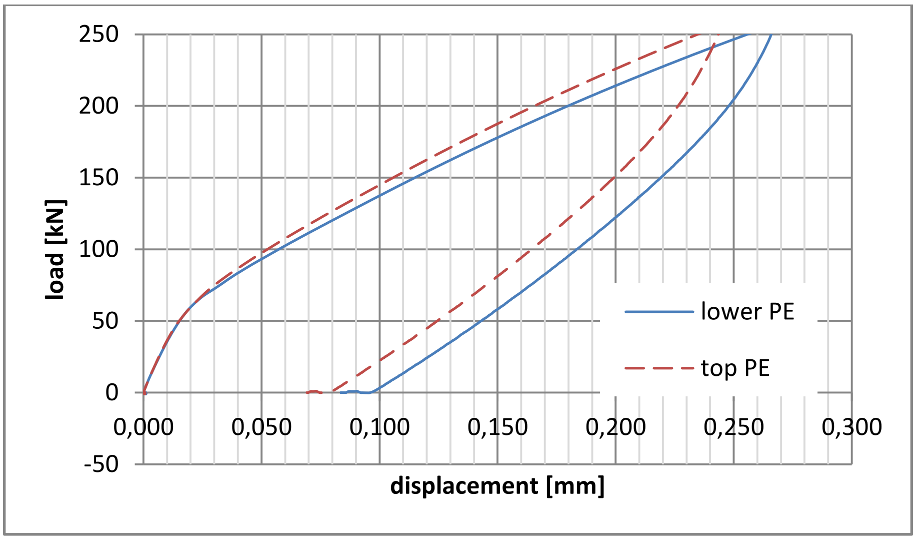
(a) Araldite 8 °C



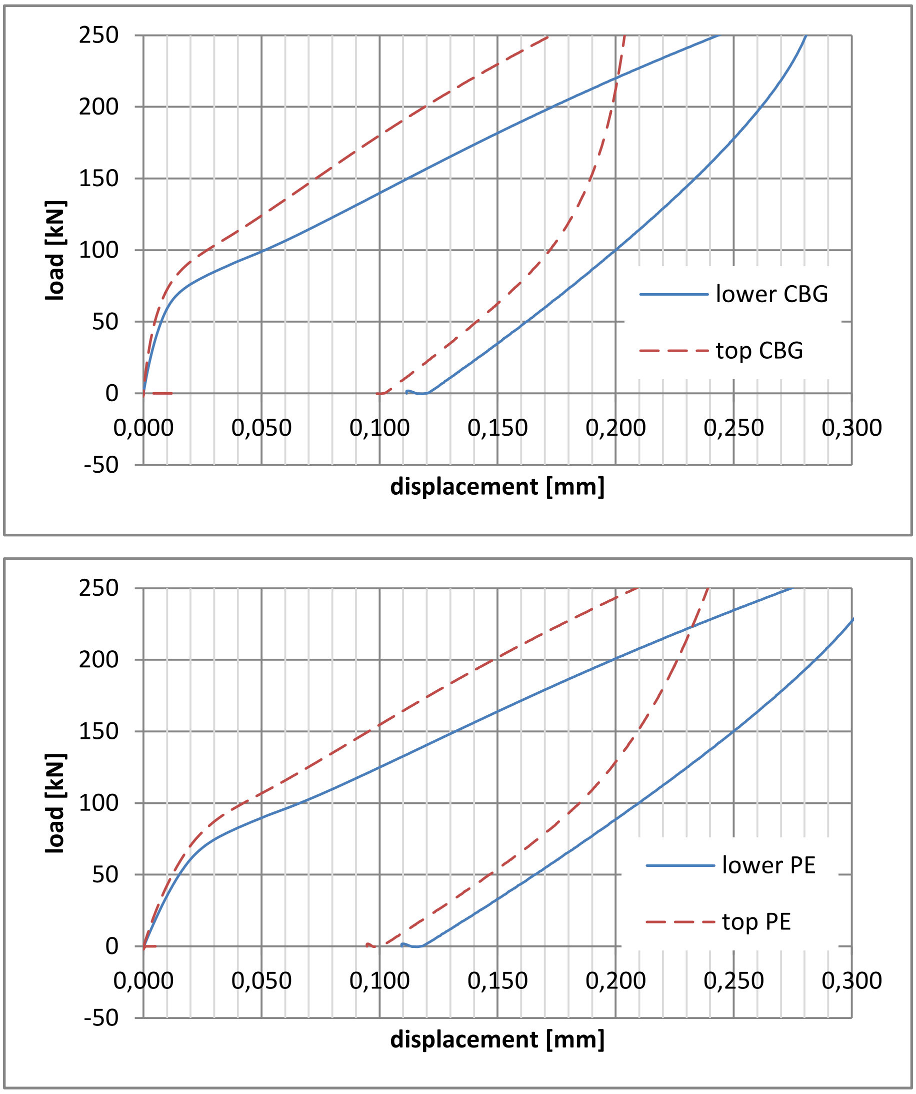


(b) Araldite 16 °C

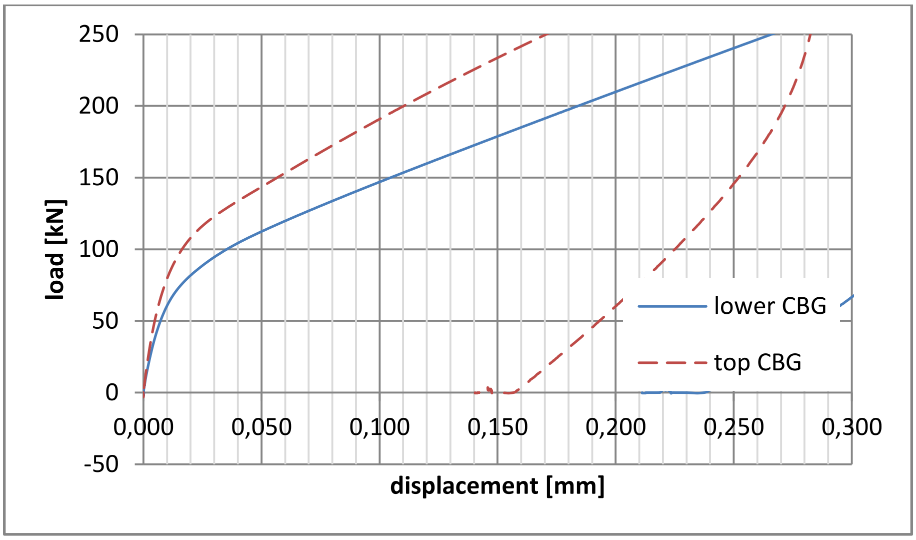


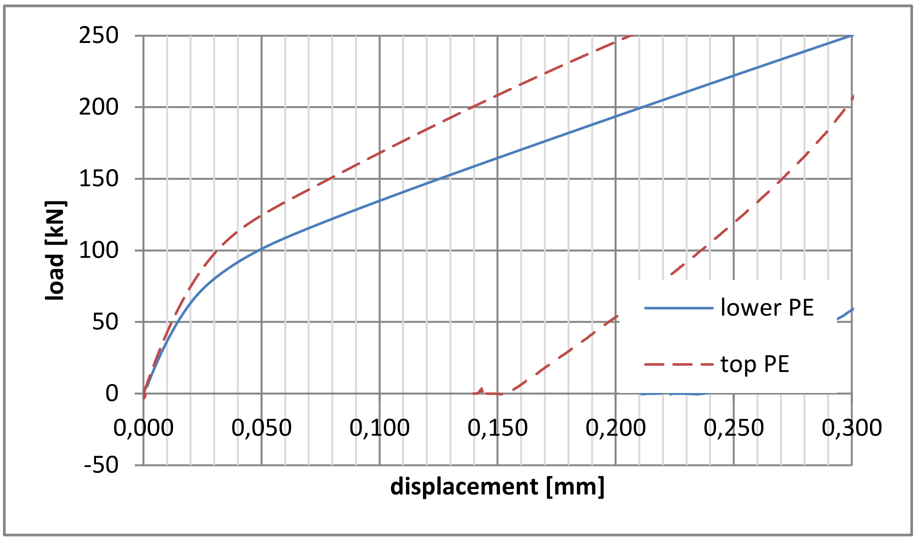


(c) Araldite 24 °C

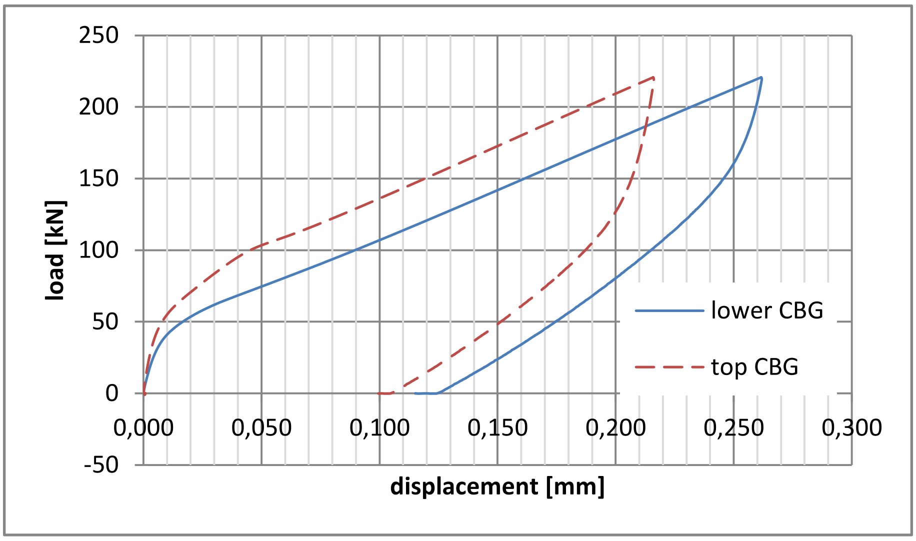


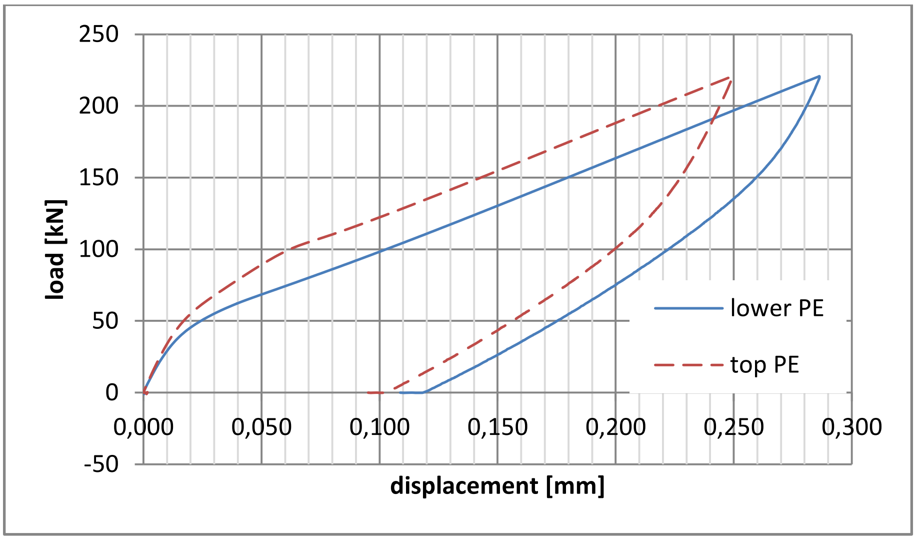
(d) Edilon Dex-R2K 8 °C



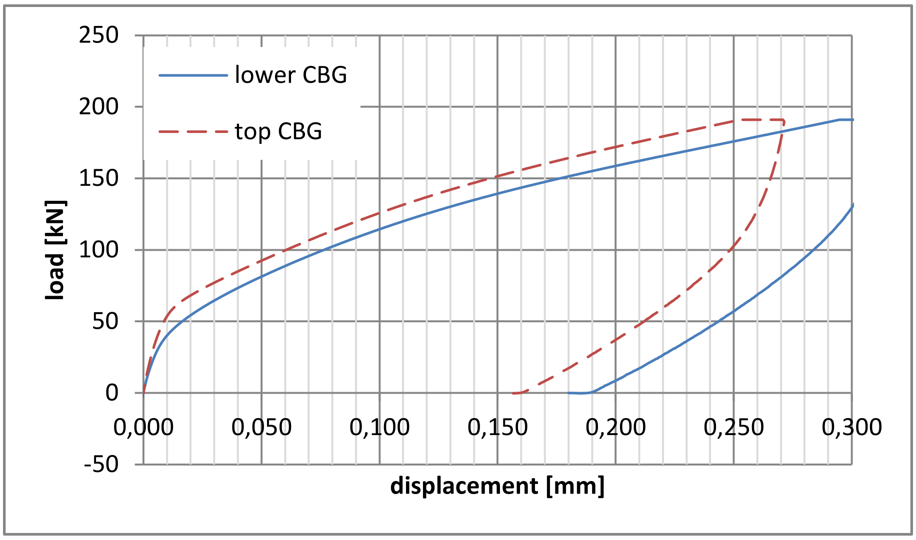


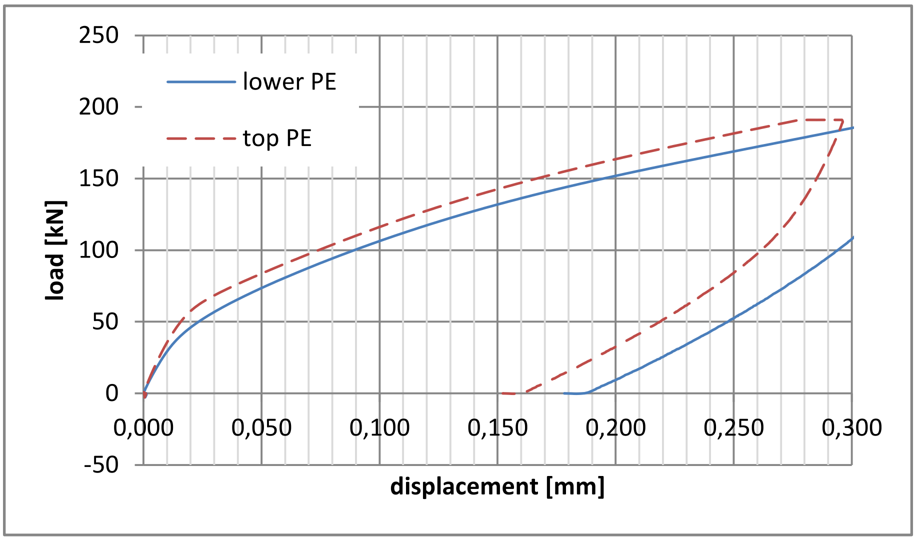
(e) Edilon Dex-R2K 16 °C



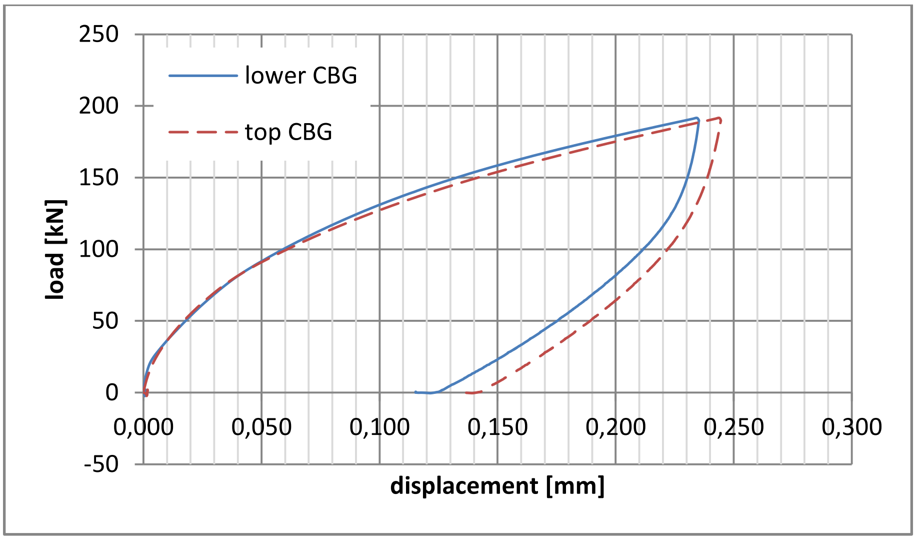


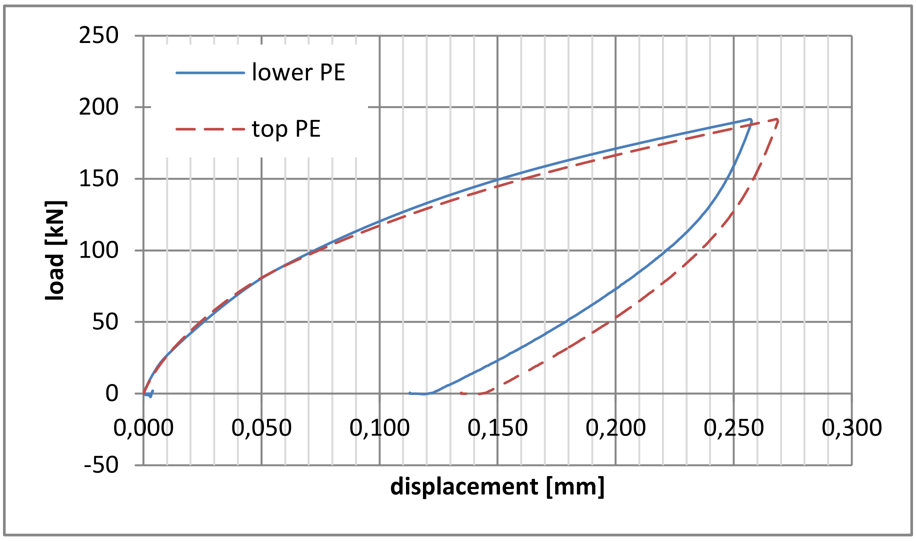
(f) Edilon Dex-R2K 24 °C



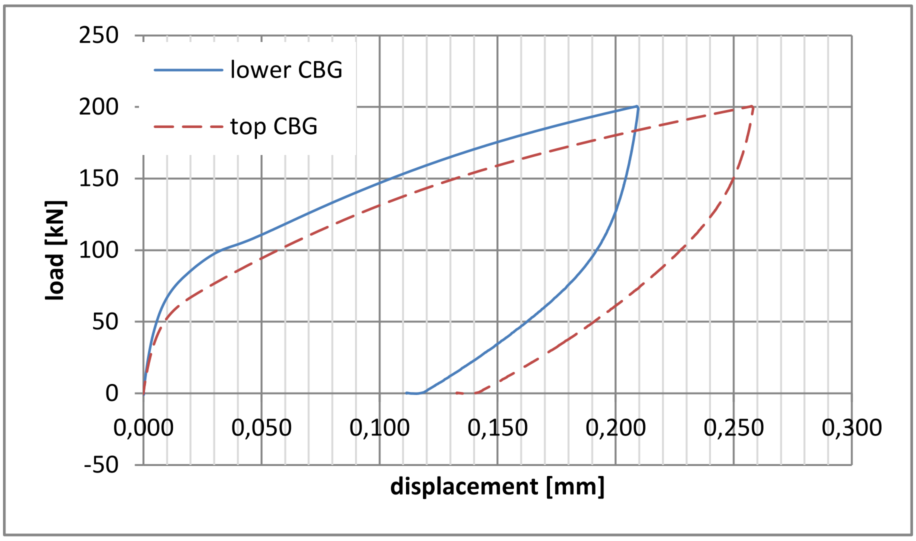


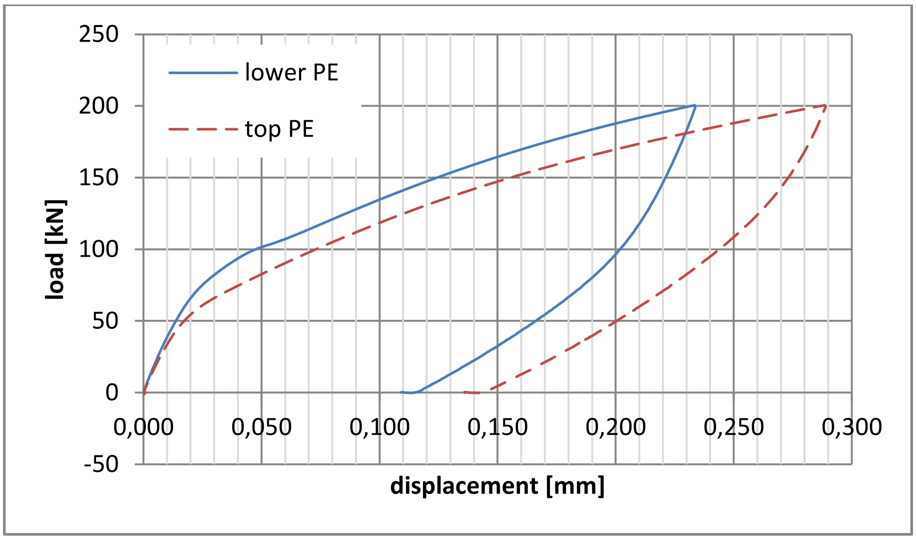
(g) Edilon Dex-G20 8 °C



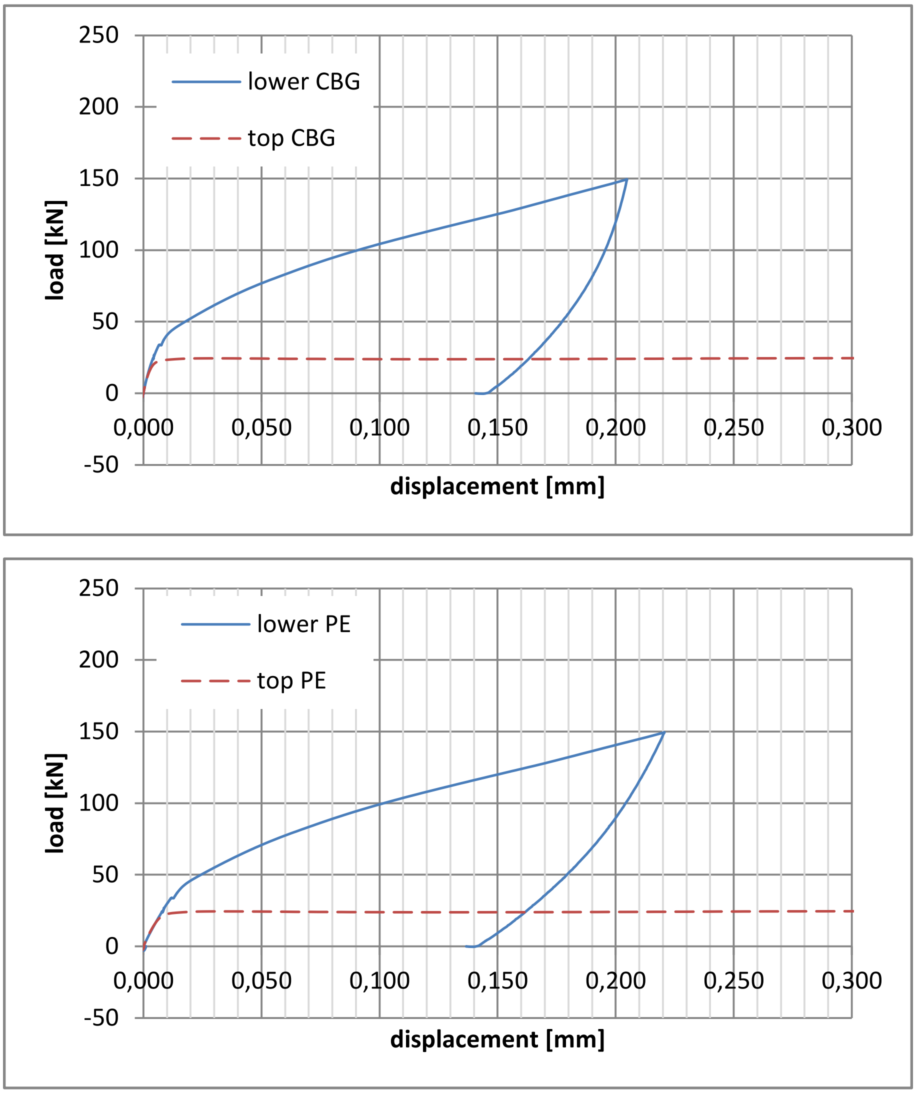


(h) Edilon Dex-G20 16 °C

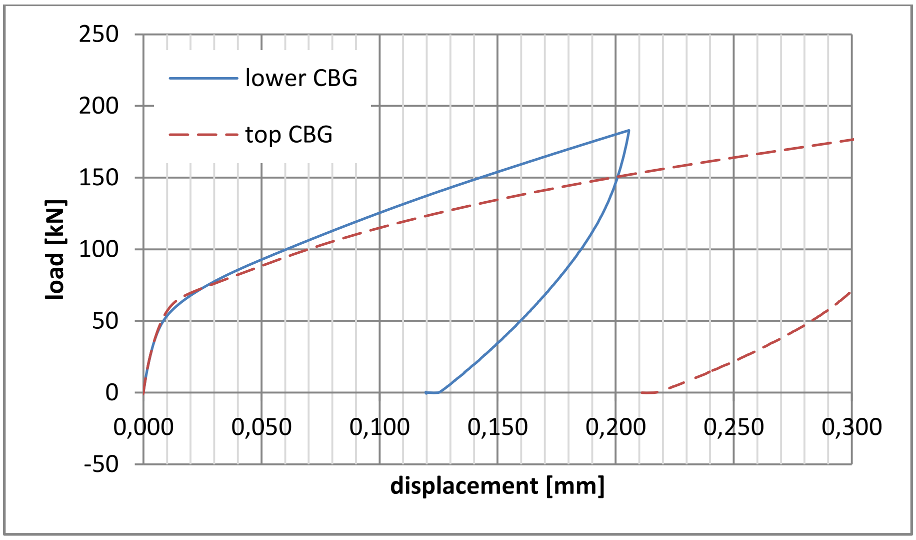


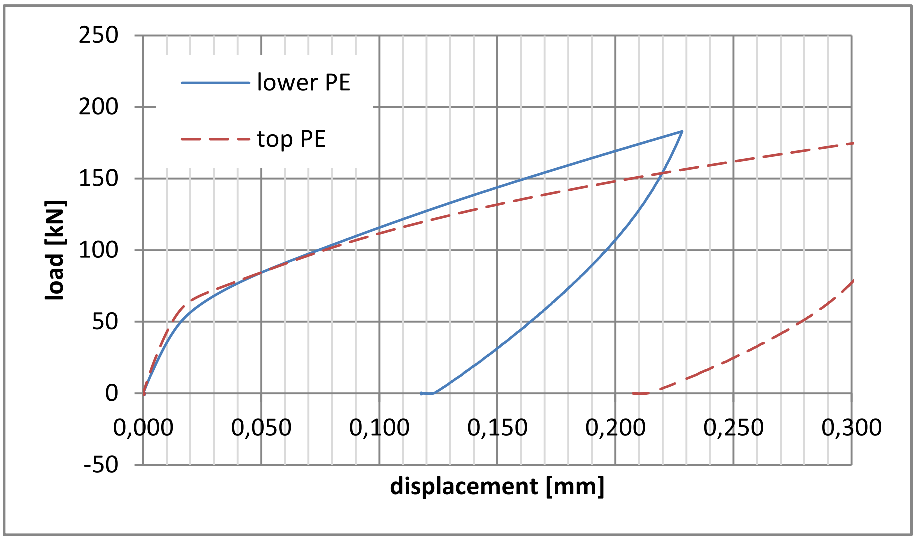


(i) Edilon Dex-G20 24 °C



(j) Sikadur 30 8 °C





(k) Sikadur 30 24 °C

Figure 2.14: Load vs displacement curves of Stage 1 - Step 2 (Initial test)

From the different resins the Edilon Dex-G20 was the easiest to inject, it has the lowest viscosity after mixing. Conversely the Sikadur 30 has the highest viscosity. This is the only resin which does not flow as a liquid when filling the injection pistol. Furthermore what was observed during injection that applying pressure to inject it does take some time for resin to flow out of the washer. Some patience must be applied before upping the pressure of the injection pistol. Too high pressures caused the resin to sometimes escape at the back of the injection canister. Due to the possible preload that was present in the specimens caused by forgetting to loosen and retighten the nuts there is a very stiff initial response seen in some of the results.

Based on the load-displacement curves in Figure 2.14, the tensile force that was applied to reach a slip value of 0.15 mm at the center of the bolt group (CBG) and at the plate edge (PE) are listed in Table 2.7. The ratio of force for 0.15 mm at PE and at CBG are also listed in this Table. Because some of the connections had not obtained usable results, some of cells in Table 2.7 have a blank of number. The reason will be discussed in detail later.

Table 2.7: Tensile force value at the slip value of 0.15 mm of Stage 1 - Step 2 (Initial test)

Resin type	Curing Temperature	Force for 0.15mm at CBG (kN)			Force for 0.15mm at PE (kN)			Ratio of average force at PE/CBG
		Top	Lower	Average	Top	Lower	Average	
Araldite	8 °C	197	-	**197.0**	175	-	175.0	0.888
	16 °C	227	203	**215.0**	203	181	192.0	0.893
	24 °C	200	197	**198.5**	187	178	182.5	0.919
Edilon Dex-R2K	8 °C	229	182	**205.5**	201	164	182.5	0.888
	16 °C	234	178	**206.0**	208	164	186.0	0.903
	24 °C	172	141	**156.5**	154	130	142.0	0.907
Edilon Dex-G20	8 °C	151	139	**145.0**	142	132	137.0	0.945
	16 °C	154	158	**156.0**	145	149	147.0	0.942
	24 °C	159	175	**167.0**	147	164	155.5	0.931
Sikadur 30	8 °C	-	146	**146.0**	-	119	119.0	0.815
	16 °C	-	-	**-**	-	-	-	-
	24 °C	-	154	**154.0**	-	144	144.0	0.935

As this is the first formal testing stage after the initial attempt's, several things have occurred during the tests that impact the results. These will be discussed for the different temperatures. The lessons learned from these mistakes are summarized in the check list for the test procedure document as Appendix A in this report and it will be aided in the subsequent tests.

- 8 °C

These were the first specimens to be executed. As it turned out injecting these specimens did not go very smoothly causing the specimens to be outside of the refrigerator for over an hour. This means that the specimens will have warmed up during the procedure before being cooled again in the refrigerator. Because of this during the following injections for 16 °C and 24 °C the specimens have been covered with bubble plastic to insulate them.

Furthermore the torque wrench was not present at the time of assembly of these specimens. This means the specimens were injected when the nuts were tightened hand tight instead of the specified torque setting.

When injecting the Araldite too little amount of resin was mixed to be able to fill all the bolts. In order to finish the injection of the bolts before curing of the resin occurred additional resin was mixed. Due to the limited time available the mixing of this resin was done improperly (too little or no hardener). This lead to one bolt with a partially cured resin and one without any curing. Both of these bolts were located in one connection so the results for one of the bolt groups is unusable.

What was further observed with the 8 °C specimen was that execution of the injection of the Sikadur 30 mixture was not possible. For two of the bolts it was impossible to create a proper injection. After curing and testing of this specimen it was observed that the flow of resin had stopped already just beyond the hole in the bolt head for one of the bolts. It did not flow around the chamber of the washer to enter the bolt hole. The other bolt showed a partial filling so resin did penetrate into the bolt hole. This also meant that the result of one of the bolt groups is not usable due to improper filling. The other bolt group did have proper filling and gave normal results.

- 16 °C

For the 16 °C specimens the bolts were tightened using the torque wrench to 100 Nm. Before testing the nuts should be loosened and then done up hand tight before performing the test. This was done for the specimen of Edilon Dex-G20 but was forgotten for Araldite and Edilon Dex-R2K.

Similar issues were once again seen with the injection of Sikadur 30 for the 16 °C specimen. This time three bolts had improper filling. Testing of this sample would not lead to any relevant results so this is omitted from the results. After disassembly of the specimens once again improper flow could be seen around the washer at the bolt head side. Furthermore for one of the bolts it could be seen that the flow of resin had made it into the bolt hole but it stopped in the center plate of the specimen.

- 24 °C

For the tests at 24 °C mistakes made during the previous two temperatures were carefully checked. This resulted in no procedural errors during these test samples. However once again the Sikadur 30 resin had problems with injection. This resulted in one bolt once again not filling correctly. The same phenomenon as was seen for the 8 °C specimen was observed. This means that resin barely penetrated the washer beyond the hole in the bolt head.

Analyses

Due to various errors in the procedure of the assembly, injection and testing of the specimens the results of some tests have become unusable. This means that trends related to the temperature dependency are hard to discern.

What can be seen is the spread in results of the various resins. The spread of Araldite is lower at the highest temperature. Conversely for Edilon Dex-G20 there doesn't seem to be a clear correlation between temperature and the spread of results. For Edilon Dex-R2K the spread is large at all temperatures. The results of Sikadur 30 due to improper filling cannot be used to check for trends.

The conclusion that can be drawn from the Sikadur 30 is the filling issues could be attributed to the washer that is located behind the head of the bolt head. Injection on two separate specimens at different temperatures was halted there despite high applied pressure. The design of this washer possibly is the cause of the problems encountered here.

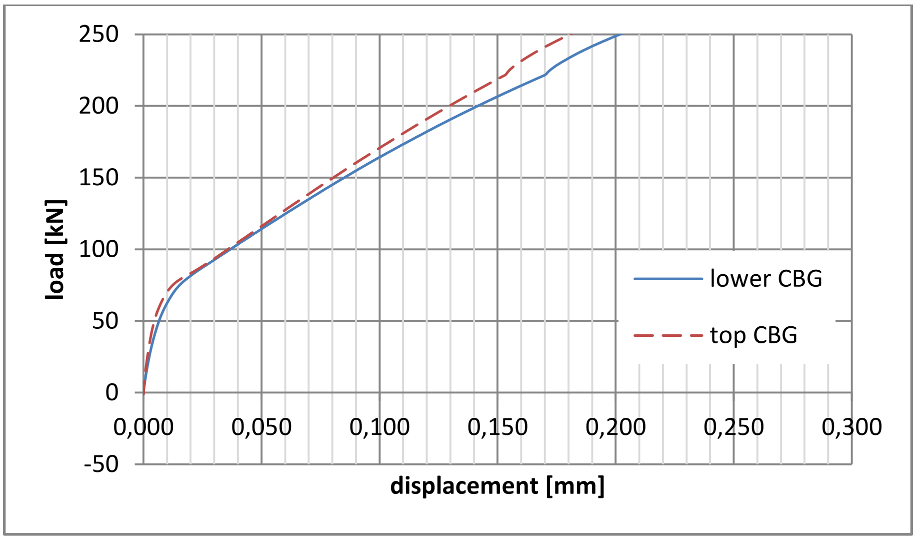
Last of all the test series at 24 °C was the one performed without any procedural errors and from this test series it can be seen that the Araldite achieves the highest strength values. The Edilon Dex-R2K which had comparable values at 16 °C clearly reached lower strength values in this series compared to 16 °C where the nuts were not loosened before testing. The influence of this mistake can thus be assumed to be of significant influence.

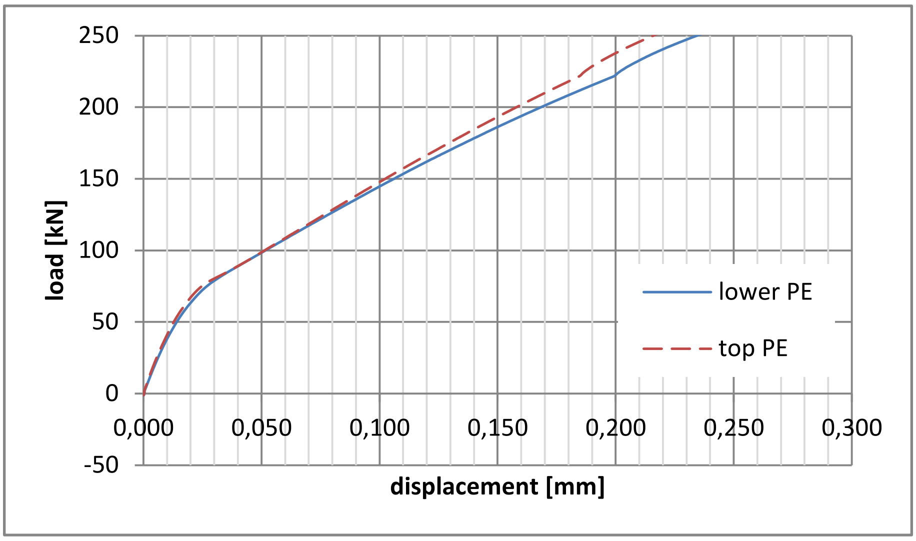
(2) Supplementary

Based on the results of these initial 12 tests, similar conclusions could be drawn as in Stage 1 - Step 1 that resin Edilon Dex-G20 and Sikadur 30 are not good choice for using as an alternative resin. For Sikadur 30, the main reason is the bad injection behaviour, and for Edilon Dex-G20 is the low strength values achieved in this step and the large creep behaviour we have known in step 1. So only two kinds of resin, Araldite and Edilon Dex-R2K, were selected for further study.

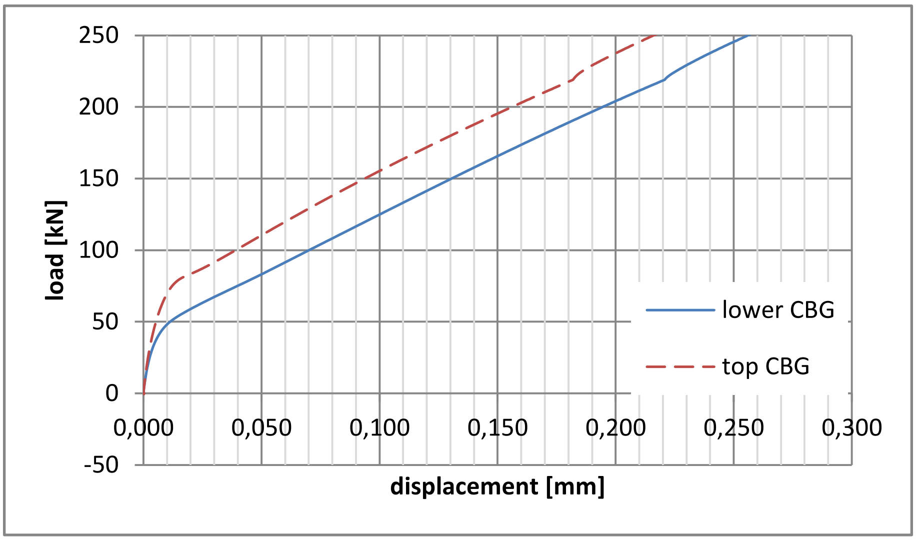
Because of the procedural errors mentioned previously that occurred during the initial tests in Stage 1 - Step 2, we decided to redo the tests with errors firstly.

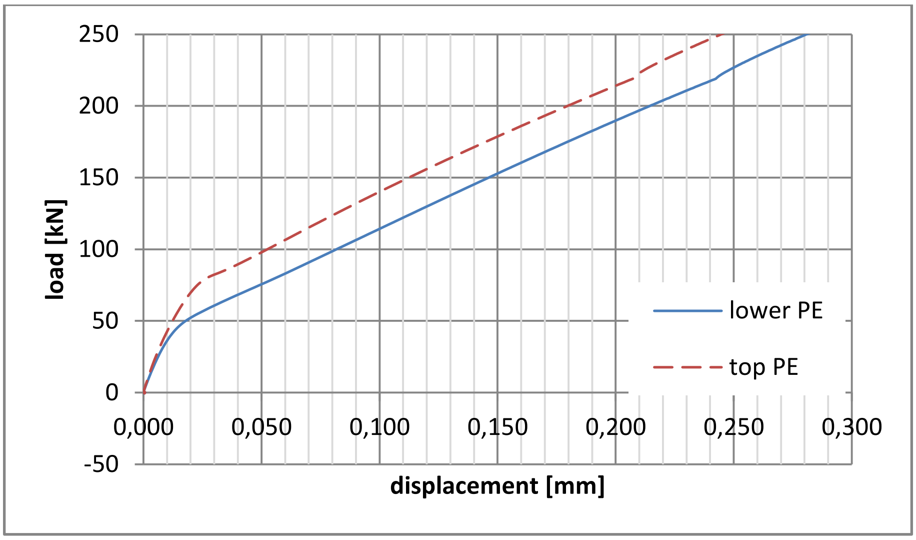
The test procedures and changed parameters in these supplementary tests have already been explained clearly in the previous text, so only test results will be listed as follows. First of all, the load-displacement curves are drawn in Figure 2.15.



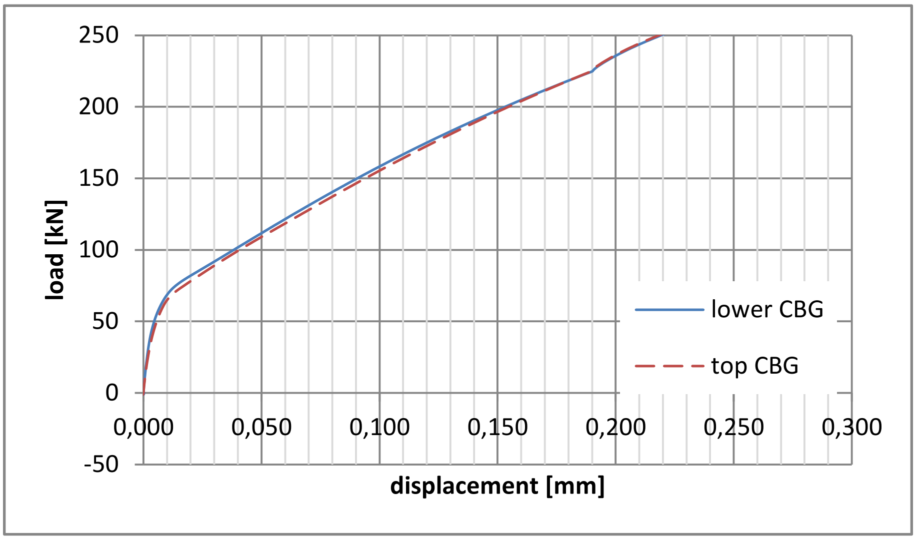


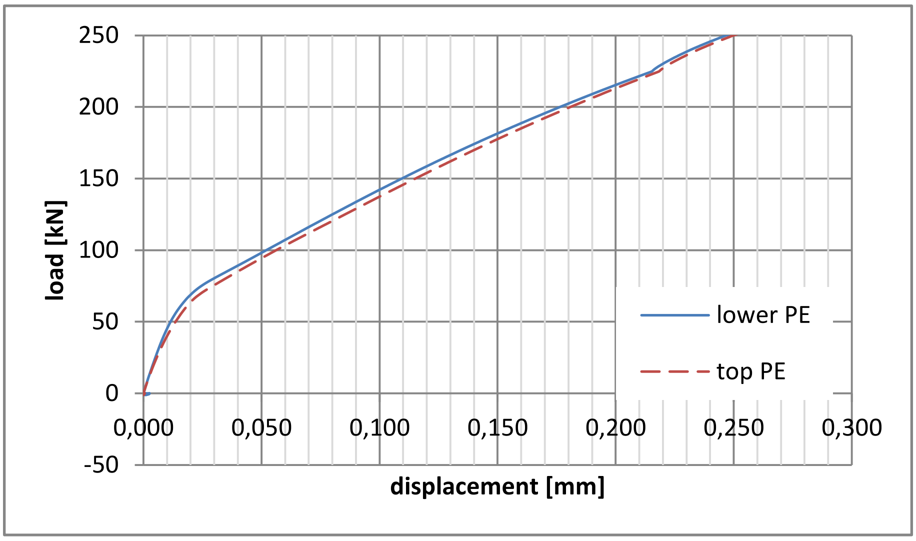
(a) Batch 1st - Araldite 16 °C



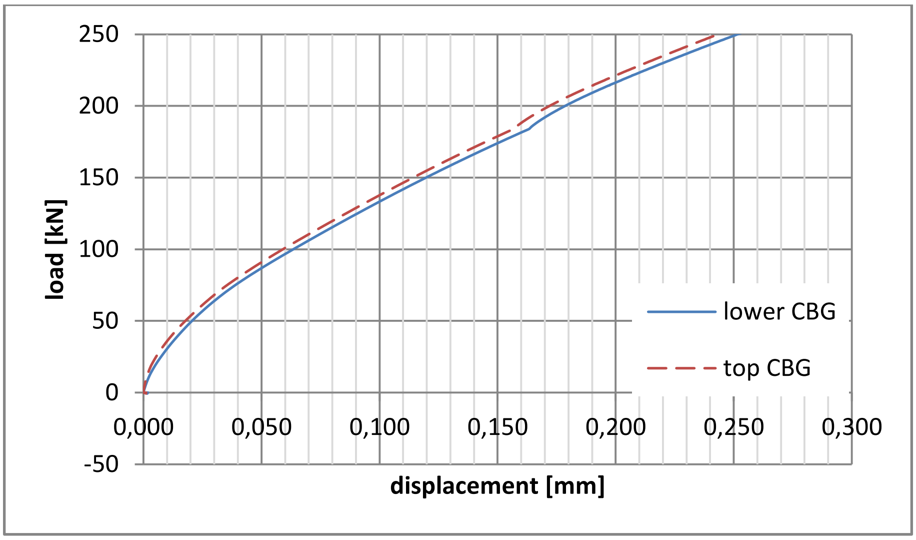


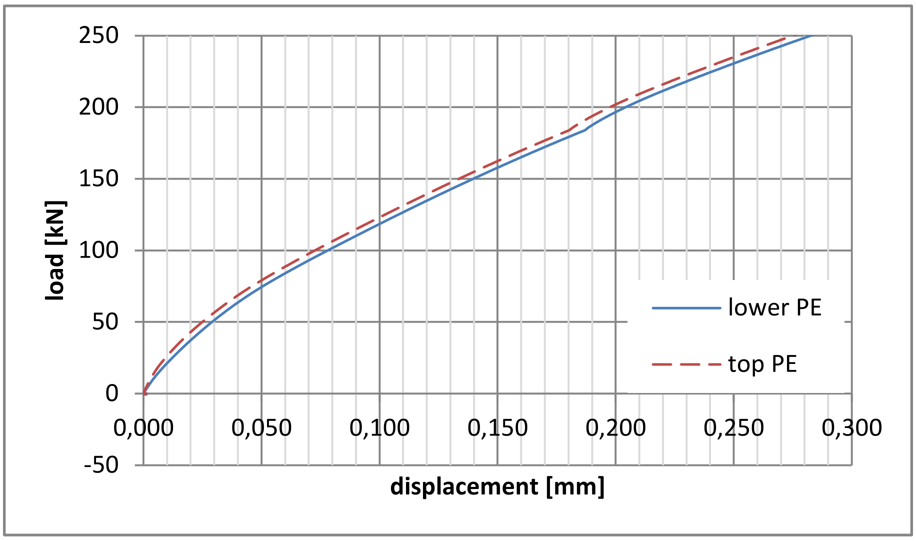
(b) Batch 1st - Edilon Dex-R2K 16 °C



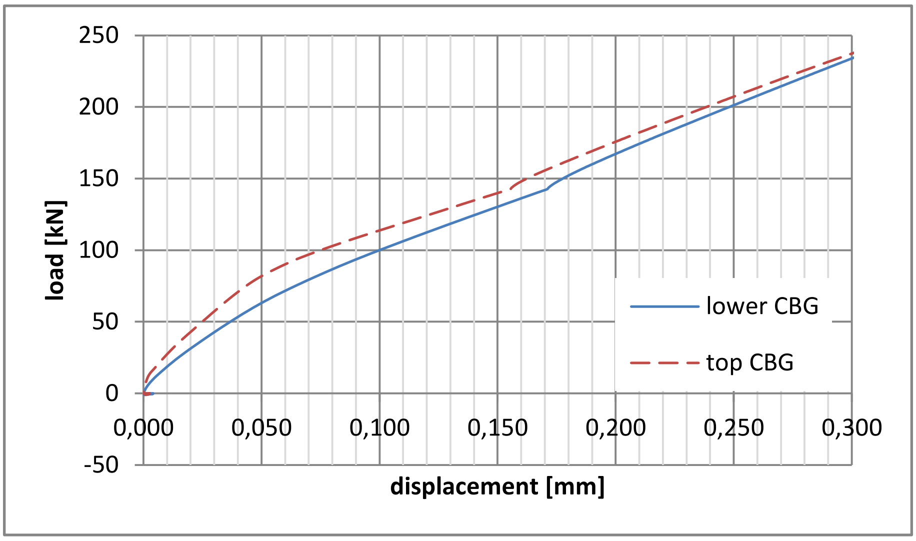


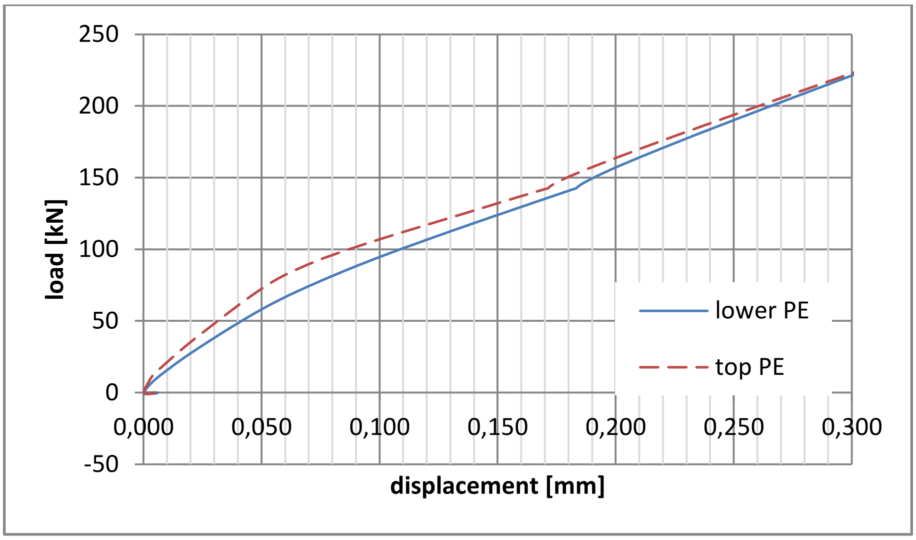
(c) Batch 2nd - Araldite 8 °C



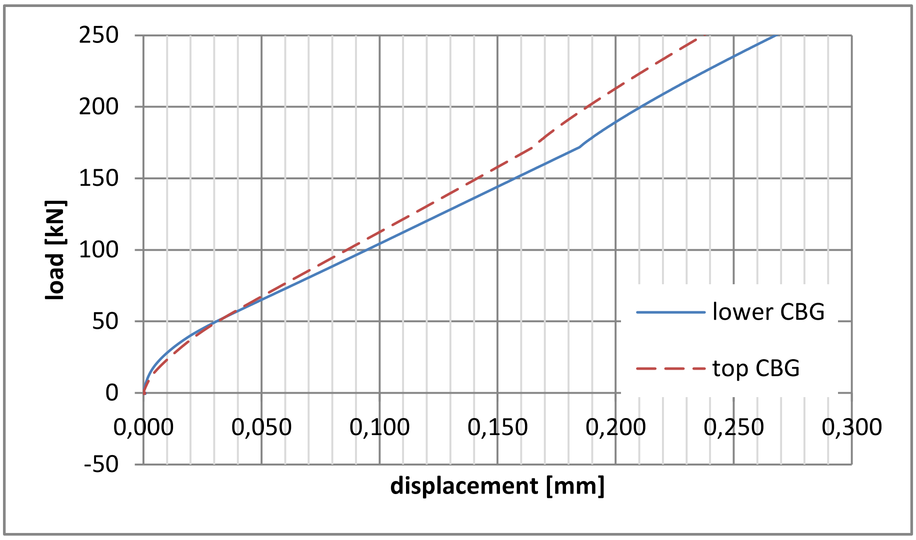


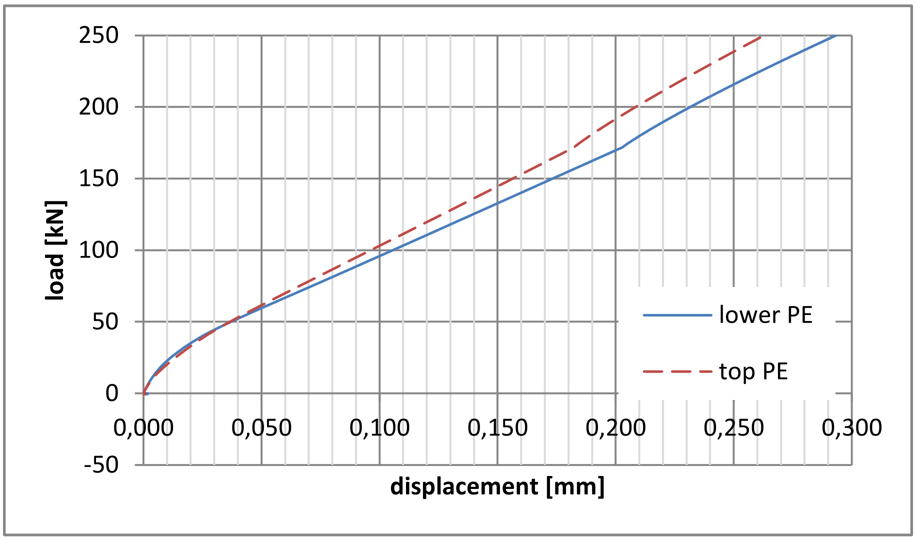
(d) Batch 2nd - Araldite 8 °C - *B-series* plates



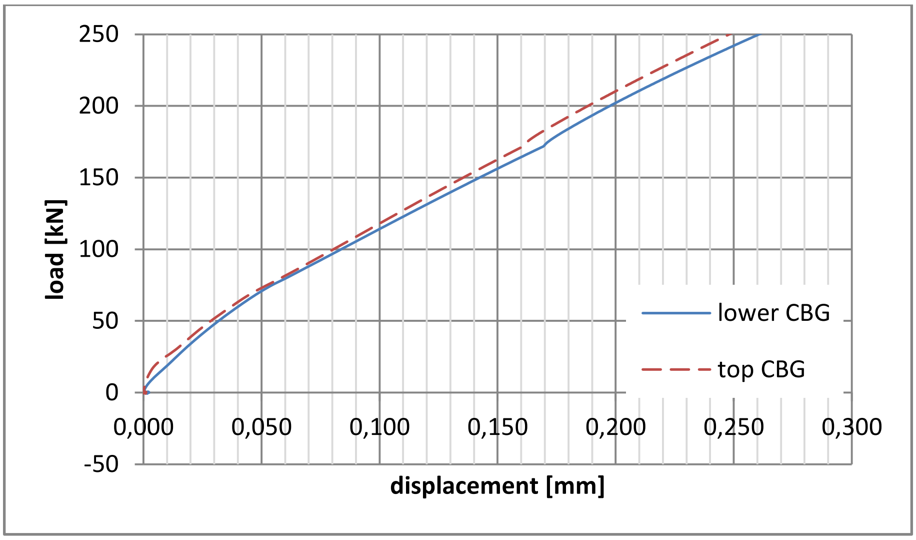


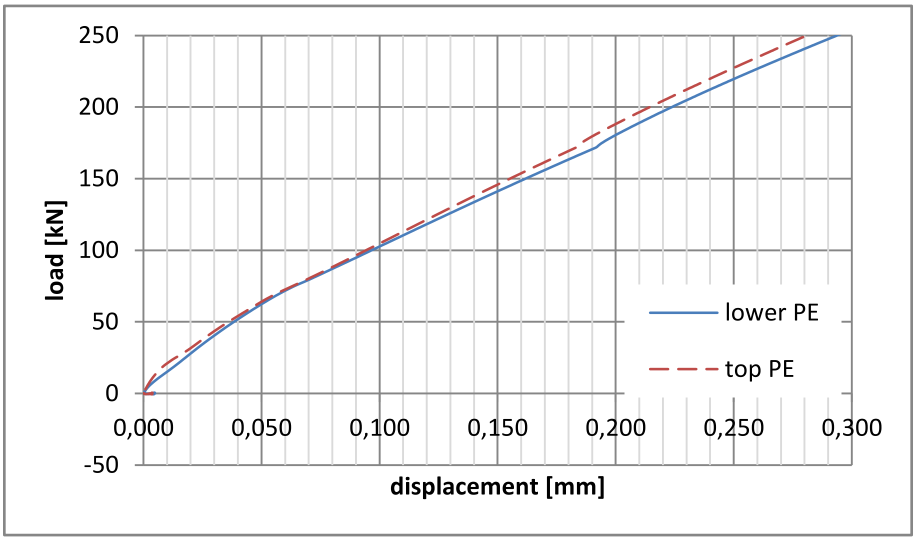
(e) Batch 2nd - Edilon Dex-R2K 8 °C



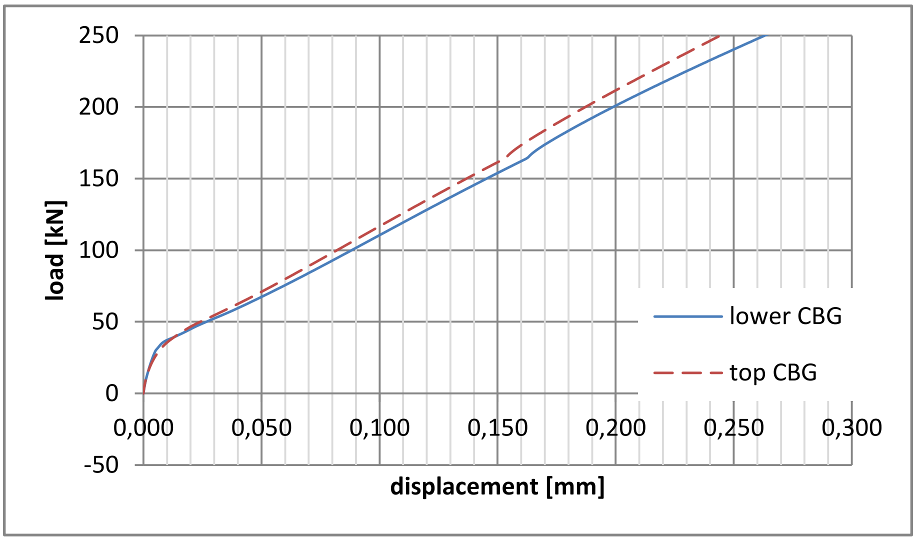


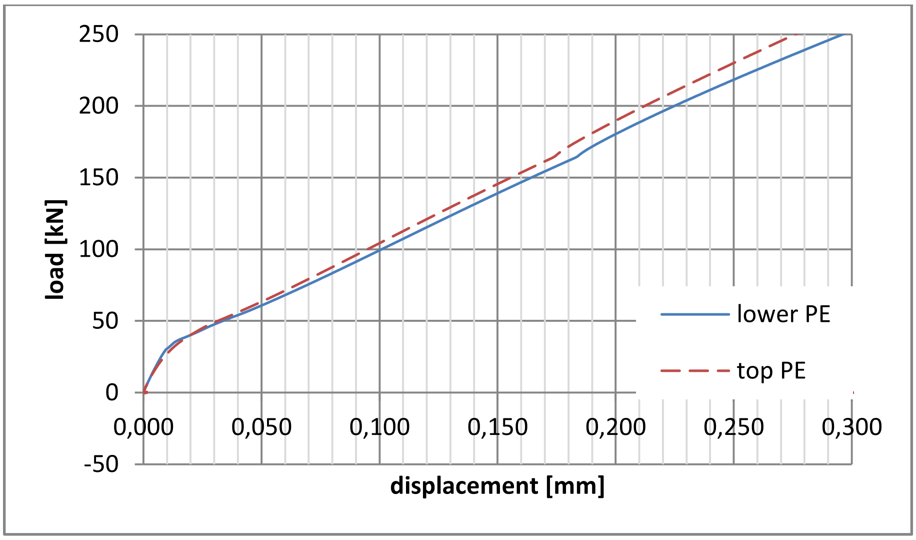
(f) Batch 2nd - Edilon Dex-R2K 8 °C - *B-series* plates



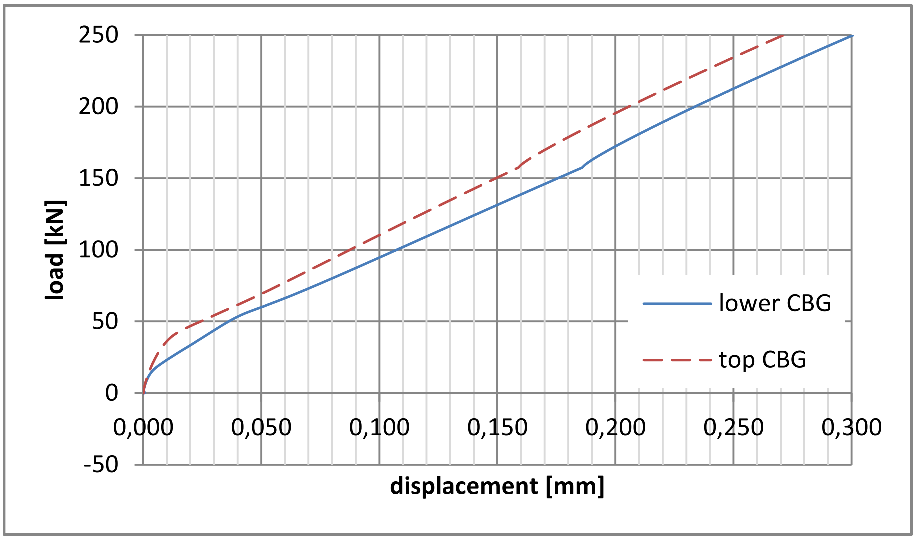


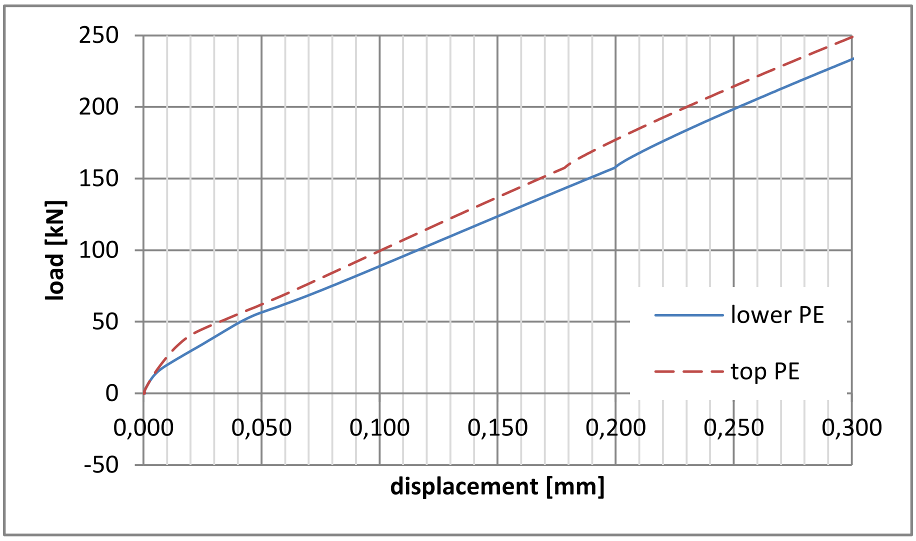
(g) Batch 3rd - Edilon Dex-R2K 16 °C - 1



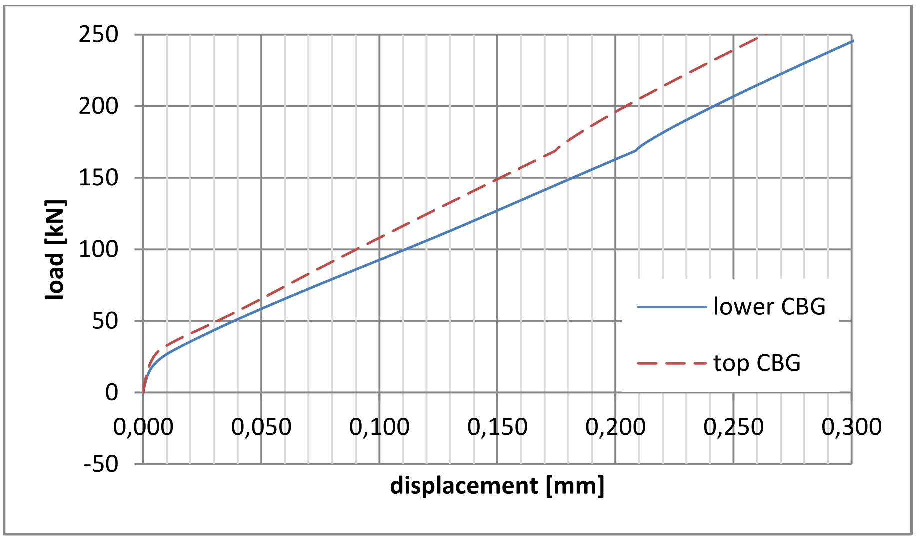


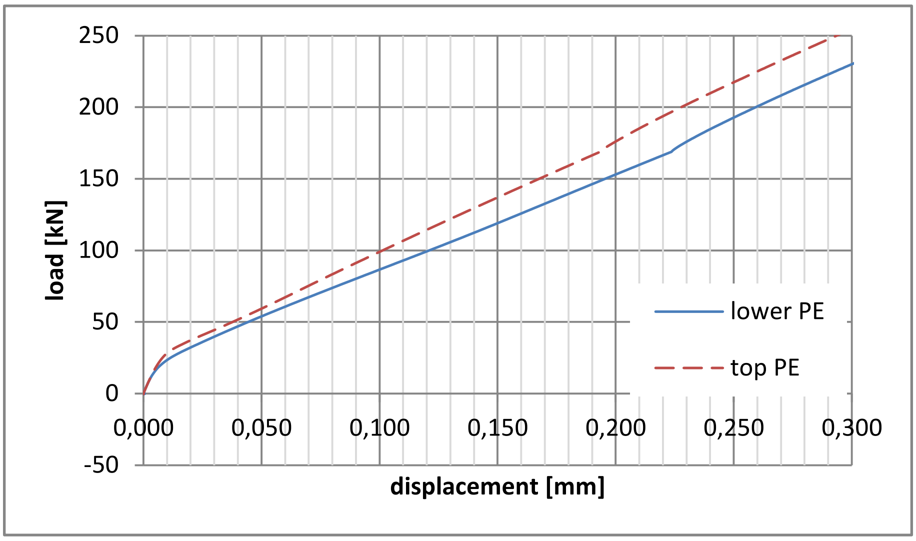
(h) Batch 3rd - Edilon Dex-R2K 16 °C - 2



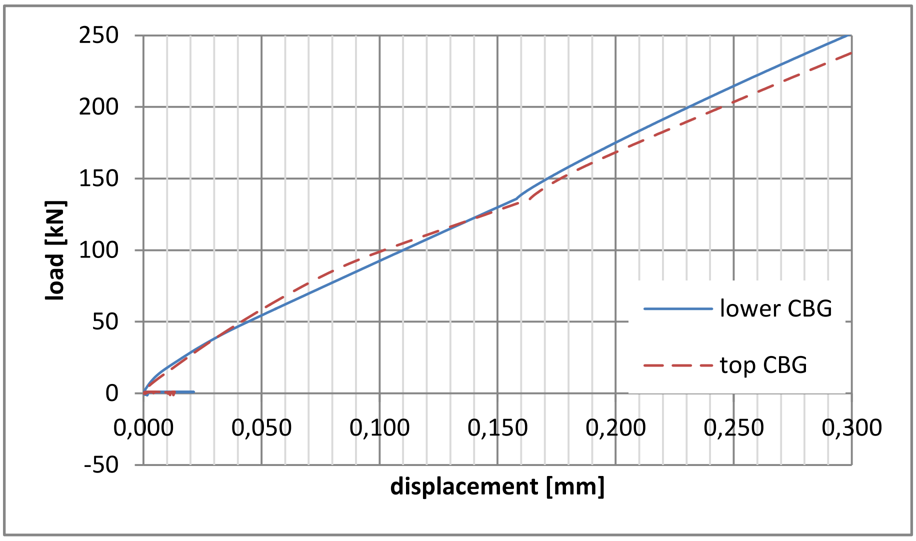


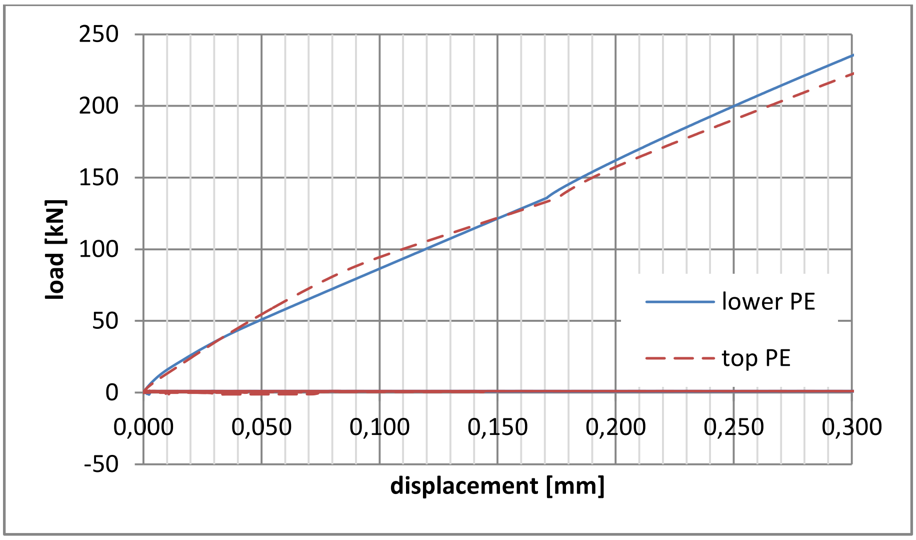
(i) Batch 3rd - Edilon Dex-R2K 16 °C - 3



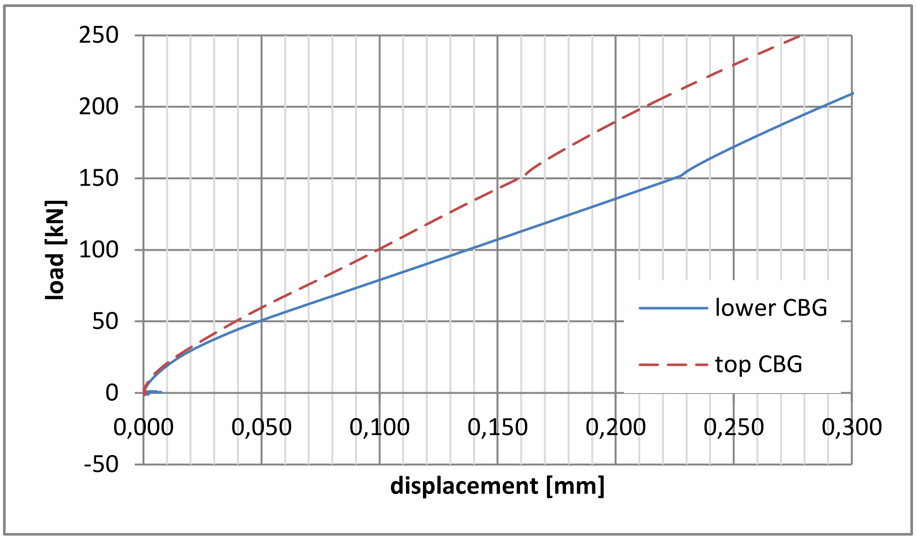


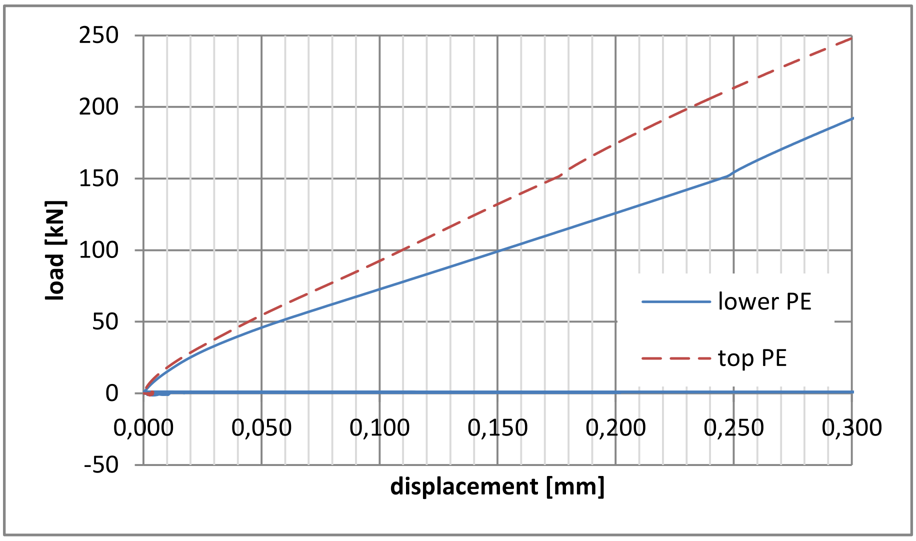
(j) Batch 3rd - Edilon Dex-R2K 16 °C - 4



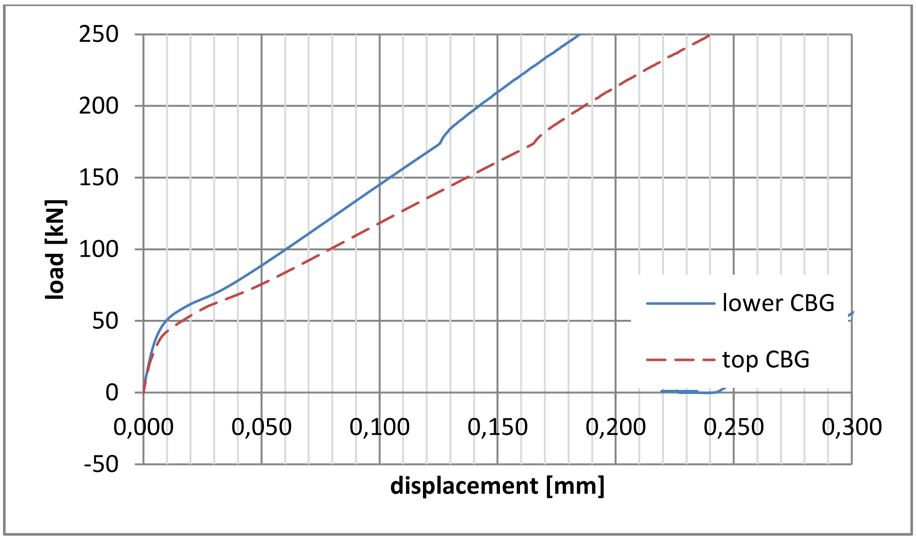


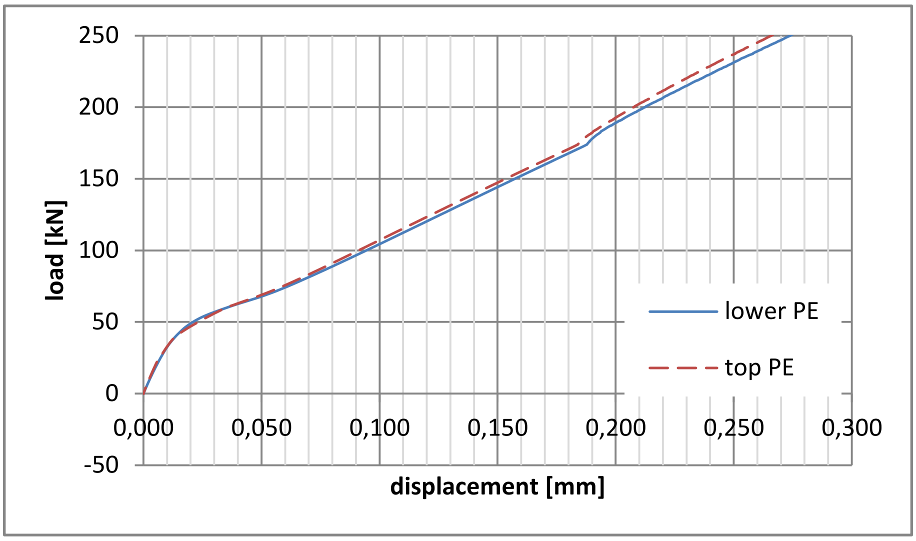
(k) Batch 4th - Edilon Dex-R2K 8 °C - 1



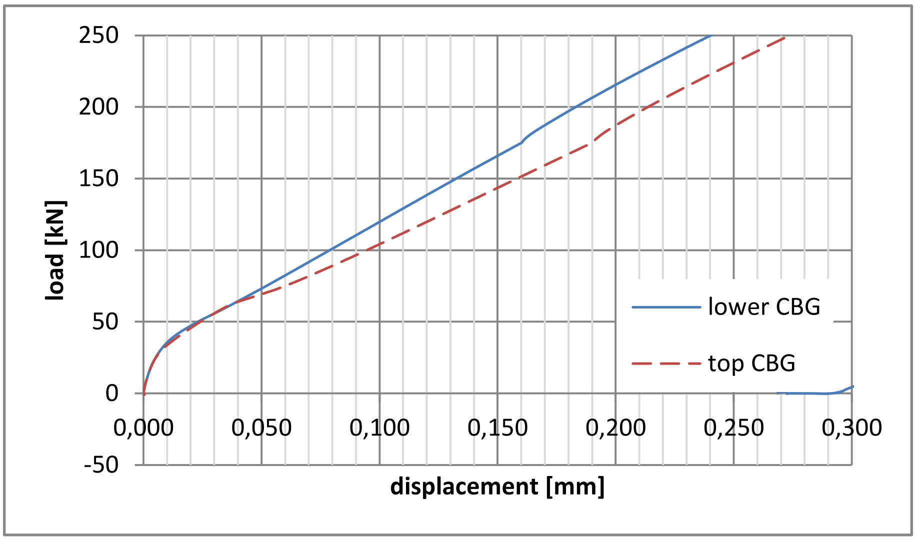


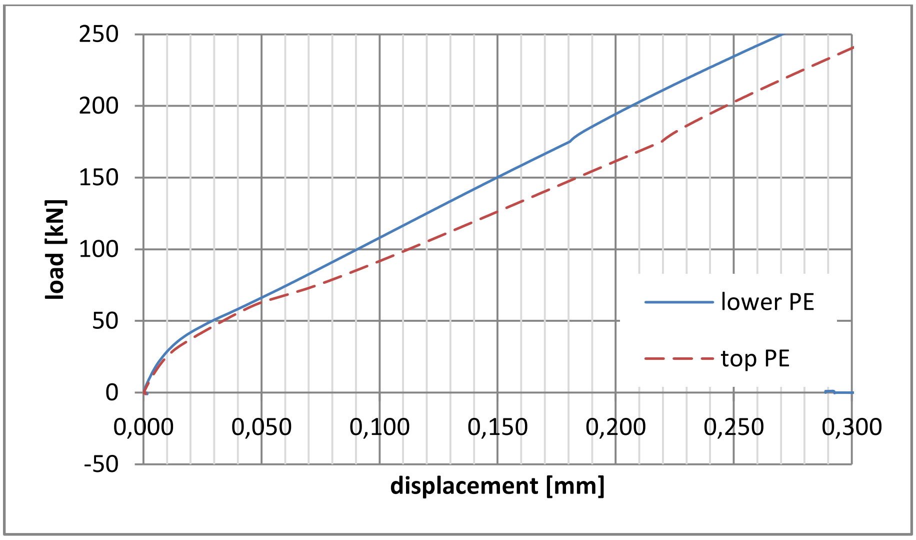
(l) Batch 4th - Edilon Dex-R2K 8 °C - 2





(m) Batch 4th - Edilon Dex-R2K 24 °C - 1





(n) Batch 4th - Edilon Dex-R2K 24 °C - 2

Figure 2.15: Load vs displacement curves of Stage 1 - Step 2 (Supplementary)

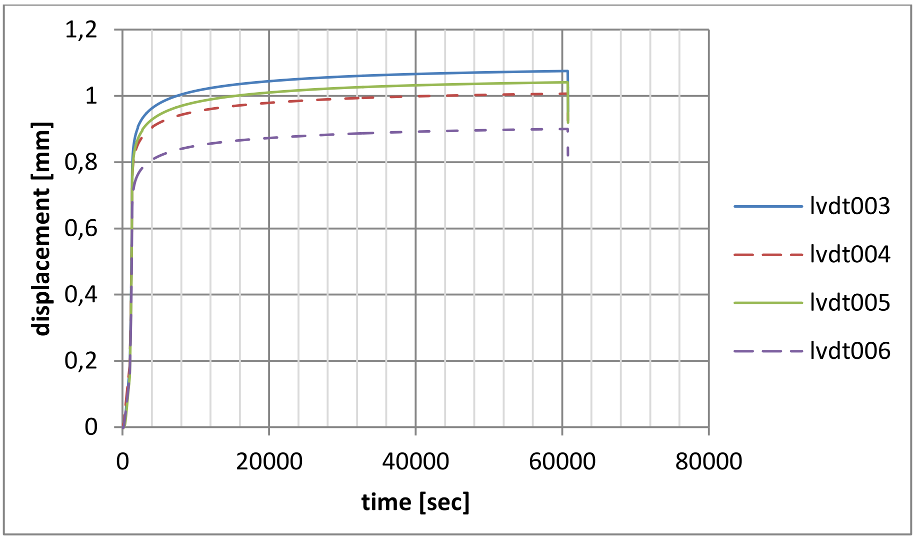
Based on the load-displacement curves in Figure 2.15, the tensile force that was applied to reach a slip value of 0.15 mm at the center of the bolt group (CBG) and at the plate edge (PE) are listed in Table 2.8. The ratio of force for 0.15 mm at PE and at CBG are also listed in this Table.

Table 2.8: Tensile force value at the slip value of 0.15 mm of Stage 1 - Step 2 (Supplementary)

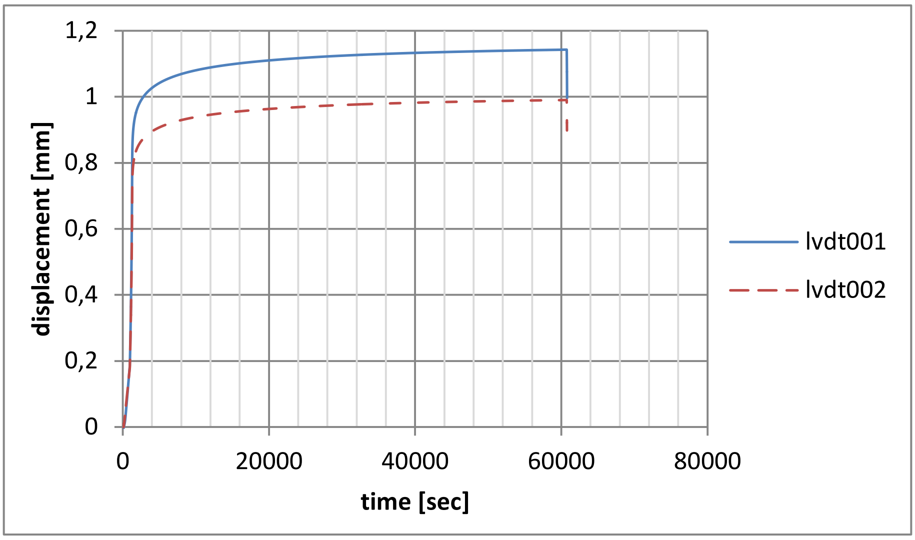
Retest Batch	Resin type	Curing Tem.	Force for 0.15mm at CBG (kN)			Force for 0.15mm at PE (kN)			Ratio of average force at PE/CBG
			Top	Lower	Average	Top	Lower	Average	
1st	Araldite	16 °C	218	206	**212.0**	193	186	189.5	0.894
	Dex-R2K		195	166	**180.5**	179	152	165.5	0.917
2nd	Araldite	8 °C	196	197	**196.5**	177	181	179.0	0.911
			178	174	**176.0**	162	158	160.0	0.909
	Edilon Dex-R2K		140	129	**134.5**	131	124	127.5	0.948
			158	144	**151.0**	144	132	138.0	0.914*
3rd	Edilon Dex-R2K	16 °C	163	156	**159.5**	145	141	144.0	0.903
			161	154	**157.5**	145	139	142.0	0.902
			150	131	**140.5**	136	123	129.5	0.922
			149	127	**138.0**	137	118	127.5	0.924
4th	Edilon Dex-R2K	8 °C	128	129	**128.5**	122	121	121.5	0.946
			143	107	**125.0**	132	98	115.0	0.920
		24 °C	161	209	**185.0**	147	144	145.5	0.786
			143	166	**154.5**	126	150	138.0	0.893

Note: * This specimen had been kept loading for 16 hours.

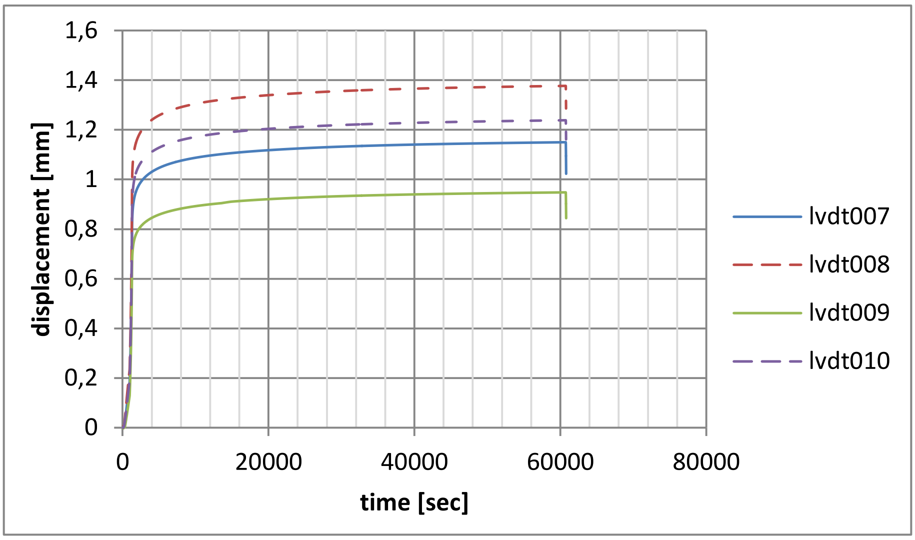
As described in the previous text about test procedure, the specimen of Edilon Dex-R2K 8 °C using B-*series* plates in the 2nd batch, has been keeping 500kN tensile value for 16 hours before unload. Therefore the displacement-time curves of this specimen is shown in Figure 2.16. The LVDTs location could be seen in Figure 2.6.



1,2
1
0,8
0,6
0,4
0,2
0
displacement [mm]
0
20000
40000
60000
80000
time [sec]
lvdt003
lvdt004
lvdt005
lvdt006



1,2
1
0,8
0,6
0,4
0,2
0
displacement [mm]
0
20000
40000
60000
80000
time [sec]
lvdt001
lvdt002



1,6
1,4
1,2
1
0,8
0,6
0,4
0,2
0
displacement [mm]
0
20000
40000
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time [sec]
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lvdt008
lvdt009
lvdt010

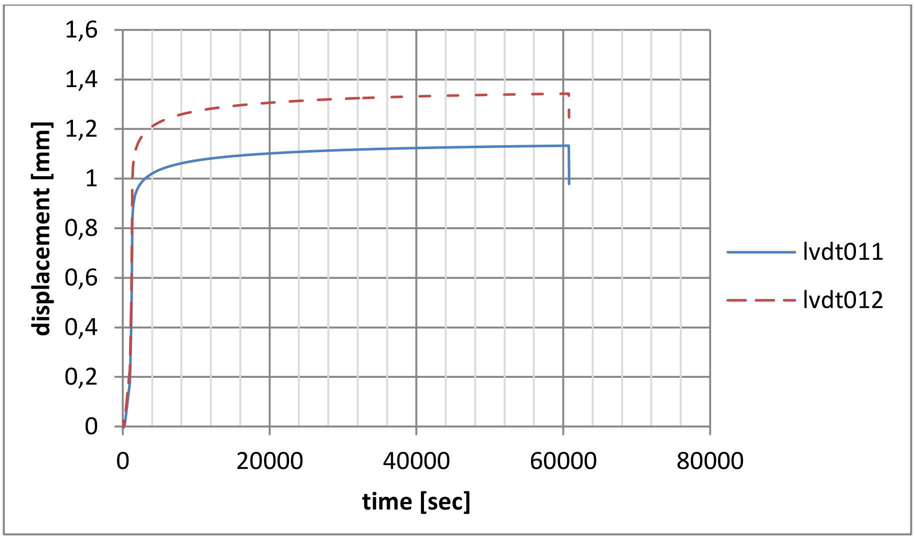


Figure 2.16: Displacement vs time curves of Batch 2nd - Edilon Dex-R2K 8 °C - *B-series*

Initial impression

Based on the results shown above, it can be concluded that the curing temperature doesn't have significant influence on the strength values achieved for Araldite. It also can be concluded that the Edilon Dex-R2K shows large spreads. One possible explanation for this spread could be the mixing method of this resin, see Figure 2.5.

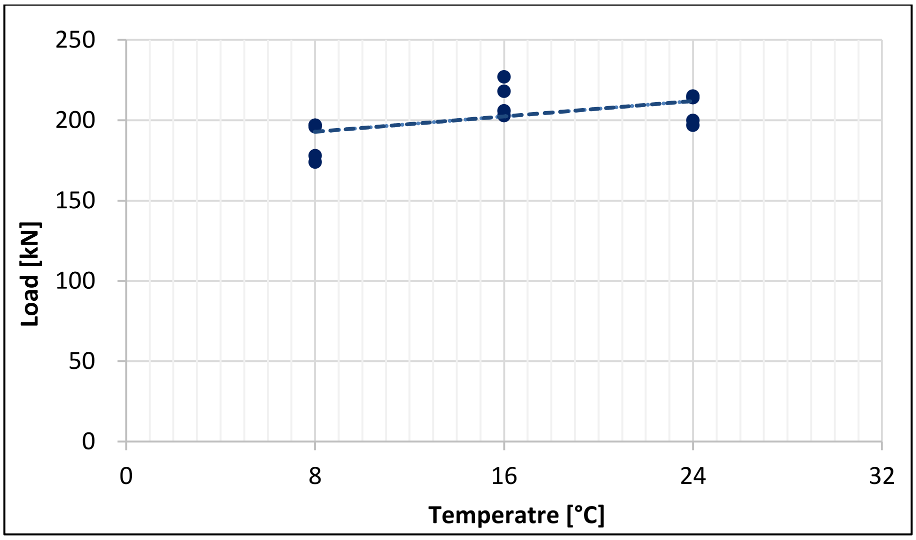
The type of the plate surface has a great influence on test results for resin Araldite. When we changed the specimen's plate surface from the *ASI-Zn* plates, the higher friction coefficient to the *B-series* plates, the low friction coefficient, the test results of resins Araldite are following to an obvious low value. But this relationship could not be clearly found for resin Edilon Dex-R2K, due to the large spread of this resin's force value results again.

When the 30 Nm torque has been used for pre-tightening instead of 100 Nm used before, the stiff initial branch found in previous results has great lower present for these tests. Therefore it can be concluded that for some kind of degree, the friction between the plate surfaces should take a influence on the force value.

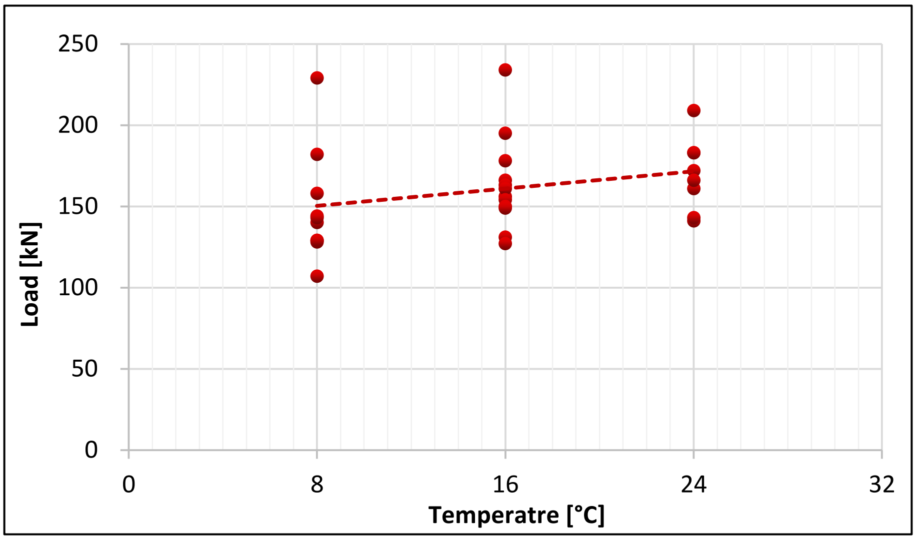
Only one specimen had been kept loading for 16 hours, see Figure 2.16. But due to the force value was so high even to 500kN, the displacements of LVDTs had reached to a large value about 1 mm, so the creep results would be no significant at all.

Analyses

Now using all the test results we had been achieved, but only two kinds of resin, Araldite and Edilon Dex-R2K are concerned. According to the tensile force value at the slip value of 0.15mm at CBG, which are listed in Table 2.4 for Step 1, Table 2.7 for Initial test of Step 2, and Table 2.8 for Supplementary test of Step 2, in total there are 7 specimens but only 13 connection's results available for Araldite, and 15 specimens, that is 30 connection's results available for Edilon Dex-R2K. Scatter diagram of these results as well as the trendline are drawn in Figure 2.17 below.



(a) Araldite



(b) Edilon Dex-R2K

Figure 2.17: Force value at the slip value of 0.15mm vs. different temperature

From Figure 2.17, we can see that for Araldite, the curing temperature actually does not have a great influence on the force value at 0.15 mm slip. Specimen at 16 °C acquired a highest force value from all, but we have been indicated before that this situation should be attributed partly to the wrong operation of forgetting loosen the pre-torque for one of a 16 °C specimen. Another arrestive lower force value has occurred at a 8 °C specimen, but we also have explained about it that it was the unique lower friction coefficient surface specimen using *B-series* plates in the tests we performed. Therefor it is the smooth surface rather not the curing temperature influence the force value. So in the end we can draw a conclusion from these limited results that the curing temperature has no influence to the force value at 0.15 mm slip for resin Araldite for simplicity.

It will be more complicated for analyzing the results of Edilon Dex-R2K. From Figure 2.17 a very large range of scatter force values can be seen apparently. A slightly increase of the force value infected by ascending of the curing temperature. But if we consider all the situations in test, the non-standard test procedure at beginning, the changing for the plate surface, and the changing for the pre-torque value, it is more difficult to come to a conclusion of the temperature tendency. So for simplicity again, we use the same conclusion as resin Araldite that the temperature tendency could be neglected also for resin Edilon Dex-R2k.

In the subsequent tests, the benchmark force value of 0.15 mm slip at CBG must be determinated first. Since we determinate to ignore the slightly influence caused by curing temperature, that is to say we will test all the following specimens at ambient temperature, which will be varied in a small range between 16 °C to 24 °C due to the heat system in the Stevin Laboratory. So we calculated the average value according to the previous tests shown in Figure 2.17, especially concerned the temperature in our laboratory, then two benchmark values have been confirmed finally, one is 200kN for resin Araldite, and another is 160kN for resin Edilon Dex-R2K.

2.2.2.2.6 Conclusions

The main conclusion getting from this step can be listed below

- When the curing temperature fall into a range from 8 °C to 24 °C, the very slightly temperature positive dependency can be neglected both for resin Araldite and resin Edilon Dex-R2K.
- Ambient temperature inside of the Stevin Laboratory will be used as the testing condition for the following tests, which would be approximately vary from 16 °C to 24 °C during the subsequent test period.
- The benchmark force value of 0.15 mm slip at CBG of the plates can be taken as **200kN** for resin Araldite.
- The benchmark force value of 0.15 mm slip at CBG of the plates can be taken as **160kN** for resin Edilon Dex-R2K.
- Resin Edilon Dex-G20 and Sikadur 30 cannot be used as an alternative resin due to the low strength values and the large creep behaviour, so these two resins will not be considered at the subsequent test.
- In order to reduce the effects of the friction between plates furthest, 30 Nm torque has been used for pre-tightening. Test procedure has been modified and it will be used as a standard testing procedure in the subsequent test.

2.2.2.3 Testing of resin loading delay (Step 3)

2.2.2.3.1 Objectives

To research the strength and stiffness properties of 2 kinds of resins selected from step 2, varying the resin curing time, while ignoring the curing temperature.

The curing temperatures is

- Ambient temperature, which has varied in a very small range during the period of experiments and the temperature value was about between 16 °C to 24 °C due to the heat system inside of the Stevin Laboratory.

The curing time are

- 6 hours
- 24 hours

Since in previous tests, most of them have been loading only about 10 to 15 minutes, so it is inadequate to know the creep behaviour of the resin injection connection. In Step 3, the loading time would be keeping at least for 90 hours to get the creep properties of these two kinds of resin.

2.2.2.3.2 Experimental plan

In total 12 specimens would be tested in Step 3, in which 2 curing time were considered. The main influencing parameters are listed in Table 2.9.

Table 2.9: Specimen details of Stage 1 - Step 3

Bolt type	Bolt size	Hole & Clearance	Resin type	Curing temperature	Curing time (hours)	Load type	Number of specimens
Non-preloaded	M20 ×80 mm	Round 2mm	Araldite	Ambient temperature	6	Step	1
						Constant	2
					24	Step	1
						Constant	2
			Edilon Dex-R2K		6	Step	1
						Constant	2
					24	Step	1
						Constant	2
Total							**12**

Note: All the specimens listed in the table above have been tested from October, 2016 to January, 2017.

2.2.2.3.3 Dimension of specimen and measurement setup

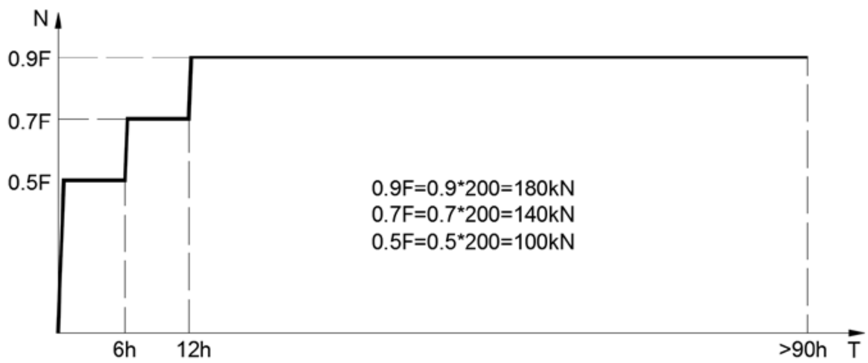
The dimension of specimens is as same as the specimens testing in stage 1 - step 1, see Figure 2.3. Therefore the measurement setup is also as same as the measurement setup using in stage 1 - step 1, see Figure 2.6.

In order to diminish the friction effect between the plates farthest, all the plates used in this step are old specimens using the *B-series* plates, which has a low friction coefficient only about 0.25.

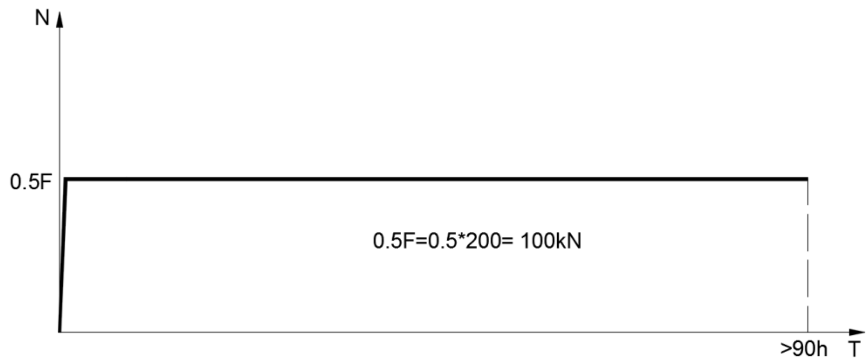
2.2.2.3.4 Test procedure

There are two load types in Step 3, one is the step load and another is the constant load. The load value depend on the test had been done, and the loading sequences are drawn in Figure 2.18 below.

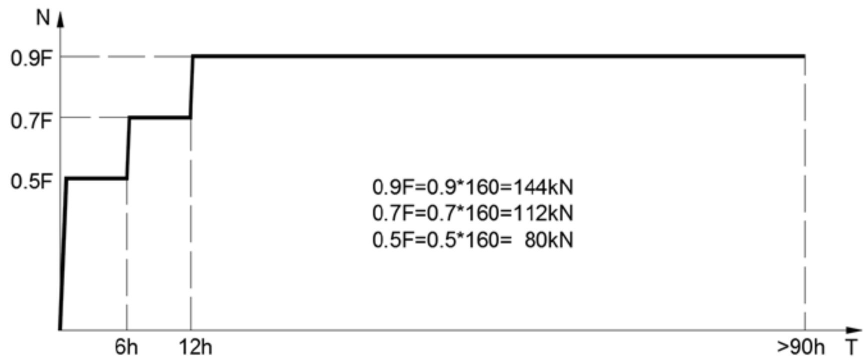
The 'F' value in Figure 2.18 means the force value for both of the connection's slip at the center of the bolt group (CBG) reach to 0.15mm, which are the benchmark values obtained at Stage 1 - Step 2, which are summarized in 2.2.2.2.6, that is **200 kN** for resin Araldite and **160 kN** for resin Edilon Dex-R2K. So the different step load value can be calculated easy and listed in Figure 2.18 also.



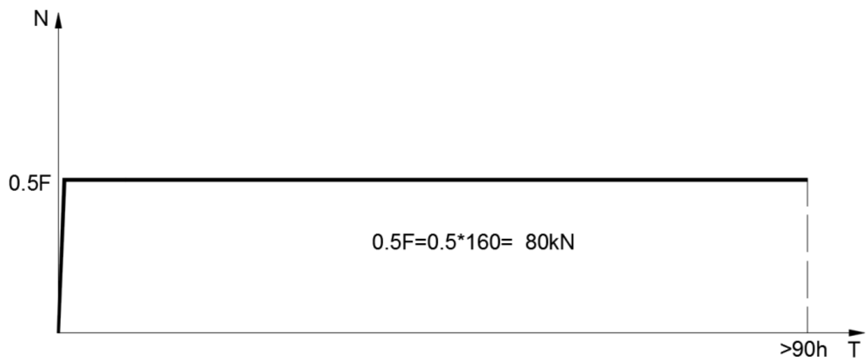
(a) Araldite - Step load



(b) Araldite - Constant load



(c) Edilon Dex-R2K - Step load



(d) Edilon Dex-R2K - Constant load

Figure 2.18: Loading sequence of Stage 1 - Step 3

Key points of test procedure are

- Force controlled with a ramp of 0.2 kN/s
- Loading sequence are shown in Figure 2.18
- 30 Nm torque applied in all of the nuts before injection and replaced by hand tightening after curing

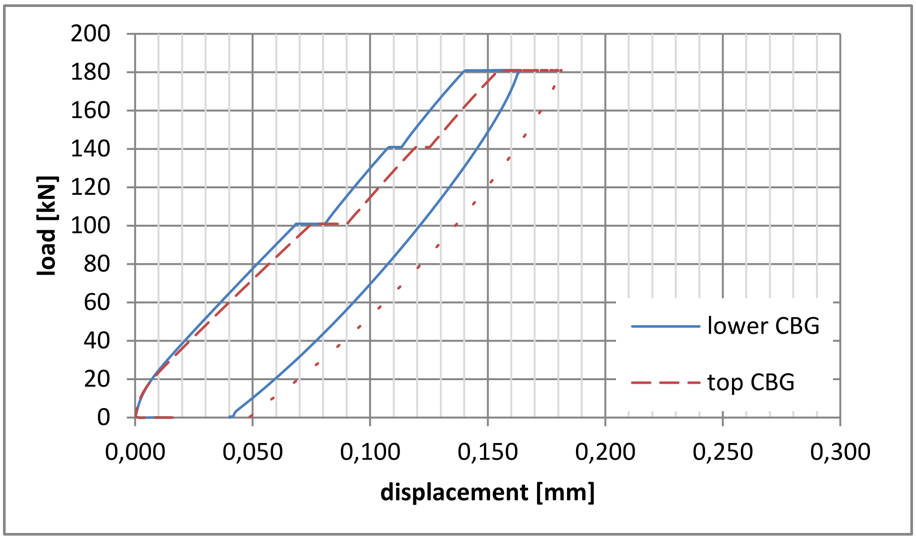
All of the 12 specimens have been loading at least for 90 hours, some of the specimens have been loading even exceed 180 hours. The name of the specimens and the duration of loading are listed in Table 2.10.

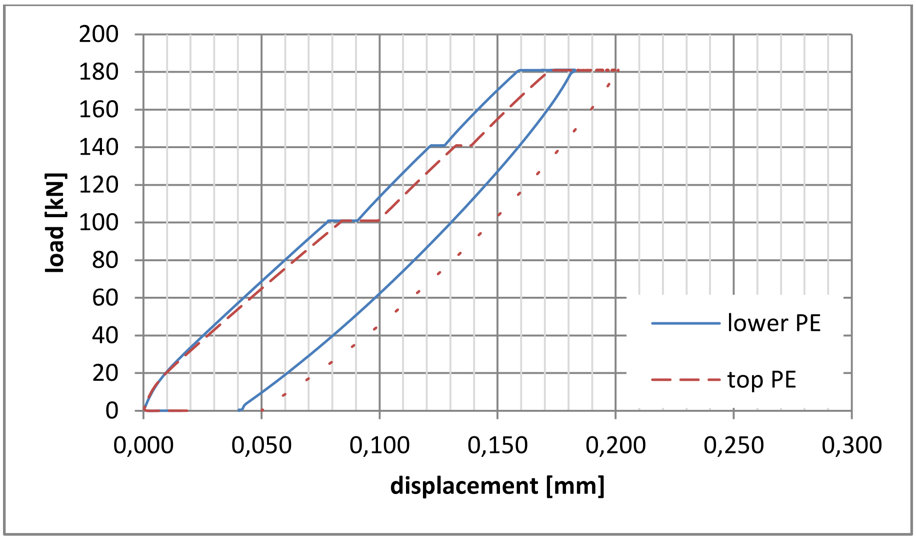
Table 2.10: Specimen's name and loading time of Stage 1 - Step 3

Resin	Load type	Name of specimen	Duration of curing (hour)	Duration of loading (hour)
Araldite	Step	Araldite-06h-1	6	185
		Araldite-24h-1	24	145
	Constant	Araldite-06h-2	6	146
		Araldite-24h-2	24	146
		Araldite-06h-2a	6	166
		Araldite-24h-2a	24	135
Edilon Dex-R2K	Step	R2K-06h-1	6	91
		R2K-24h-1	24	90
	Constant	R2K-06h-2	6	116
		R2K-24h-2	24	148
		R2K-06h-2a	6	95
		R2K-24h-2a	24	96

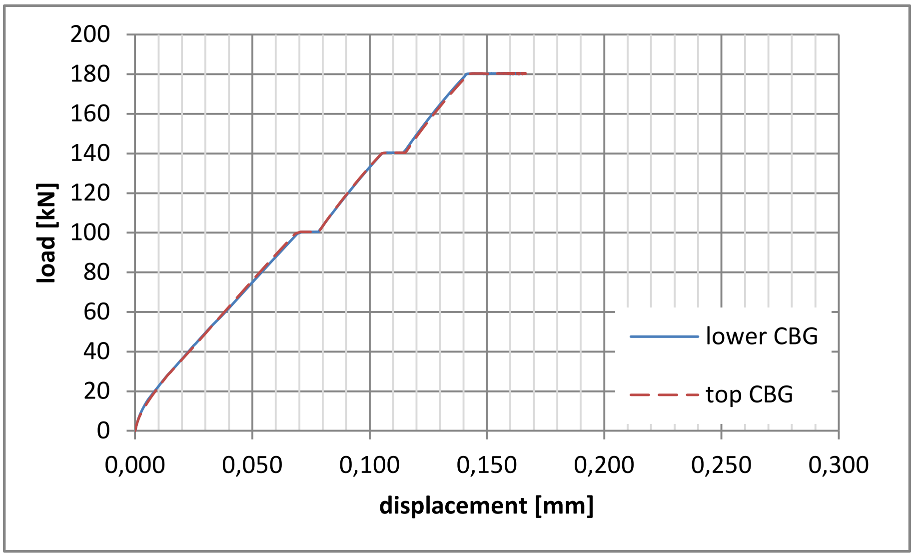
2.2.2.3.5 Test results

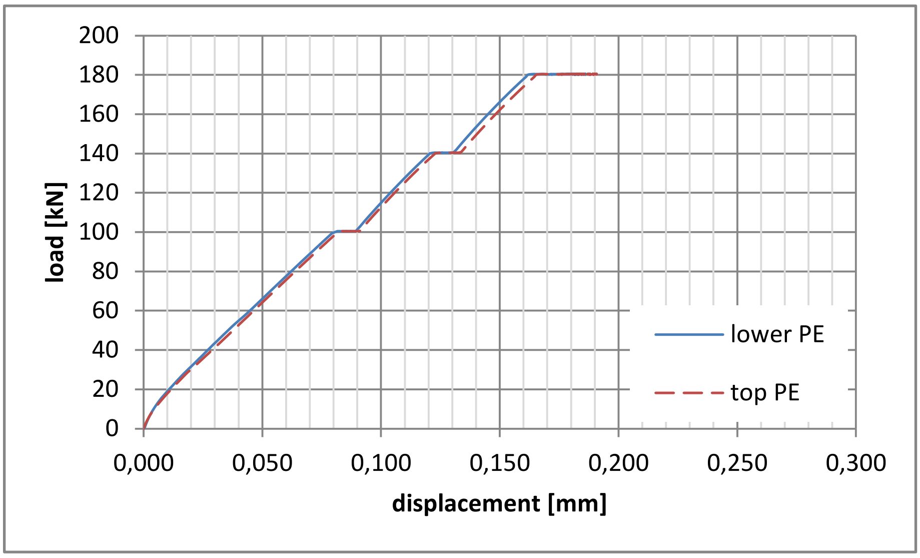
First of all, the load-displacement curves are shown in Figure 2.19. For each of them, two graphs are drawn, one is the load-displacement curves at the center of the bolt group (CBG), another is the load-displacement curves at the plate edge (PE). Only one of these specimens, the Araldite-24-1, had been forgotten to record the unloading data, but it would not influence the result analysis.





(a) Araldite-06h-1





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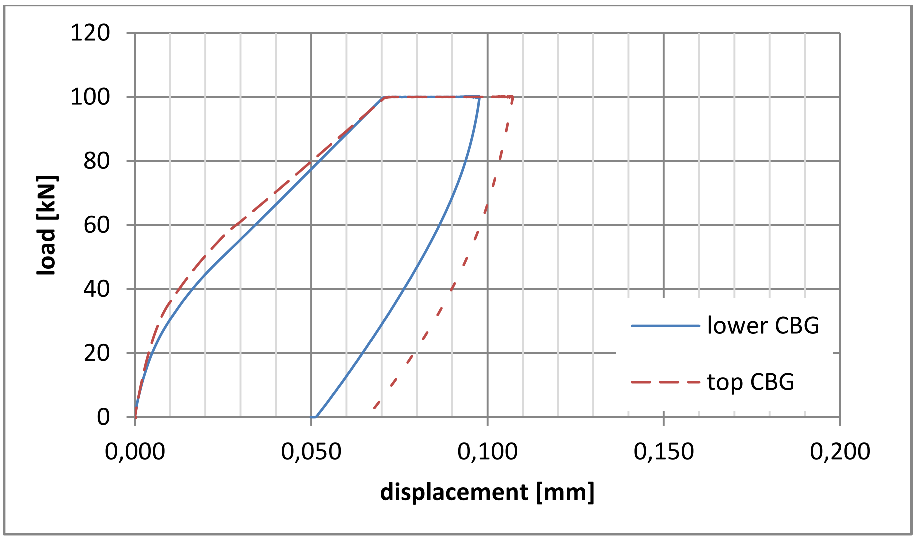

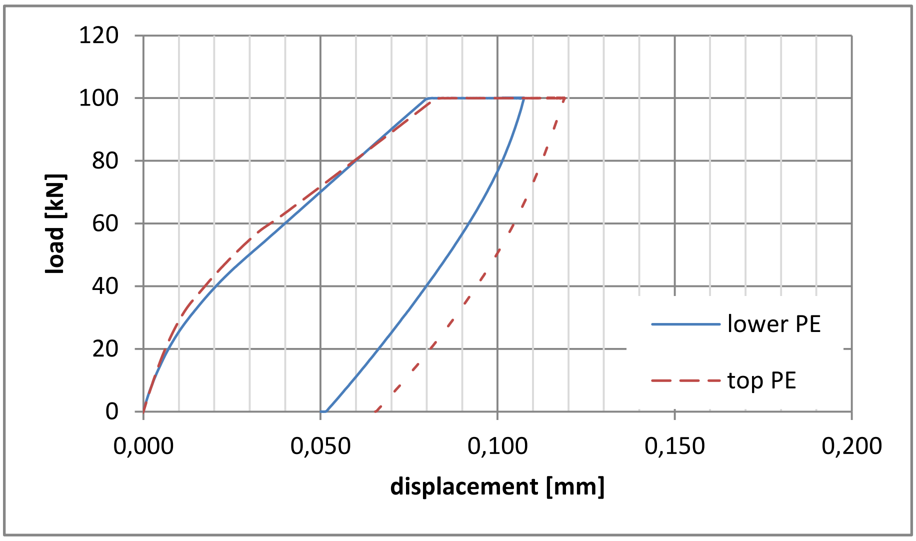

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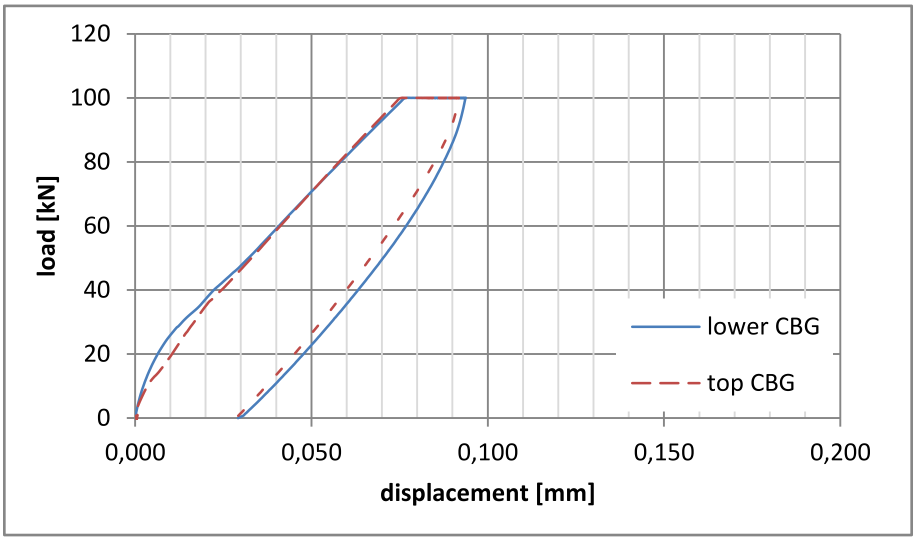

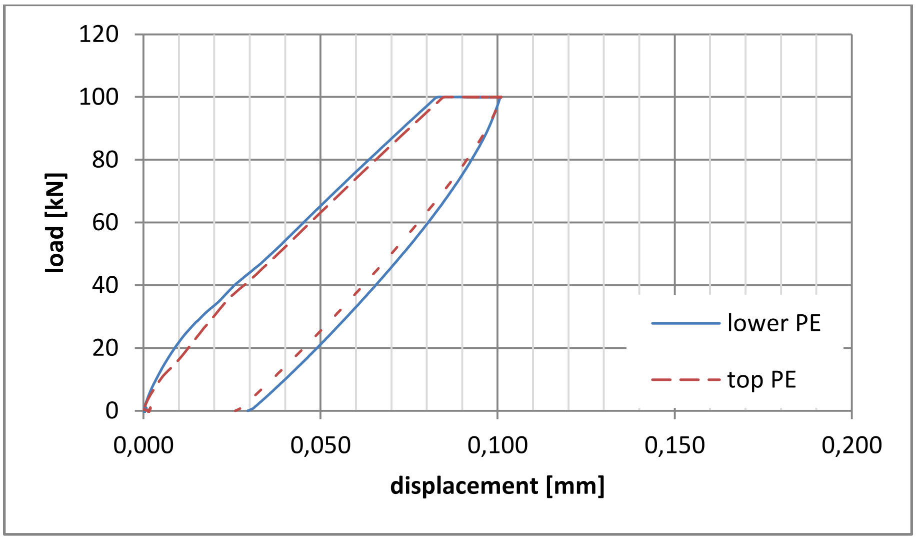

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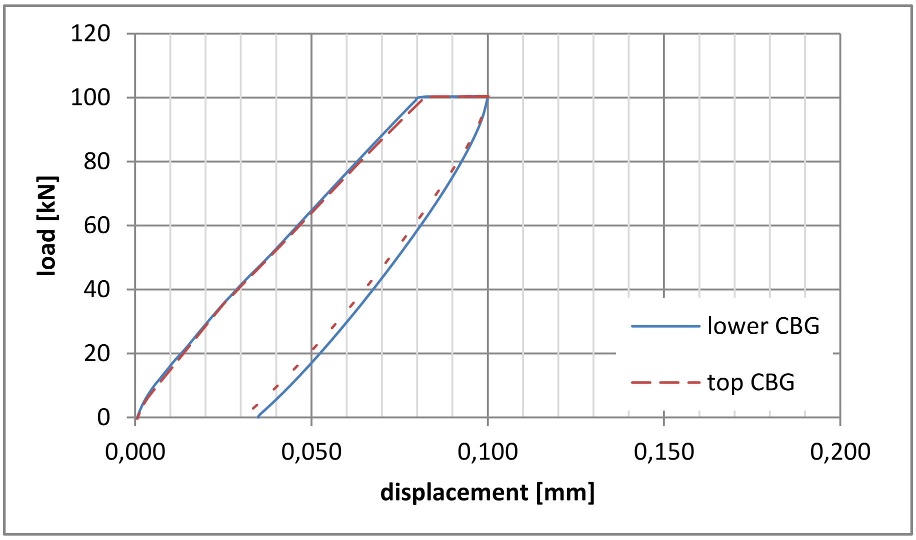

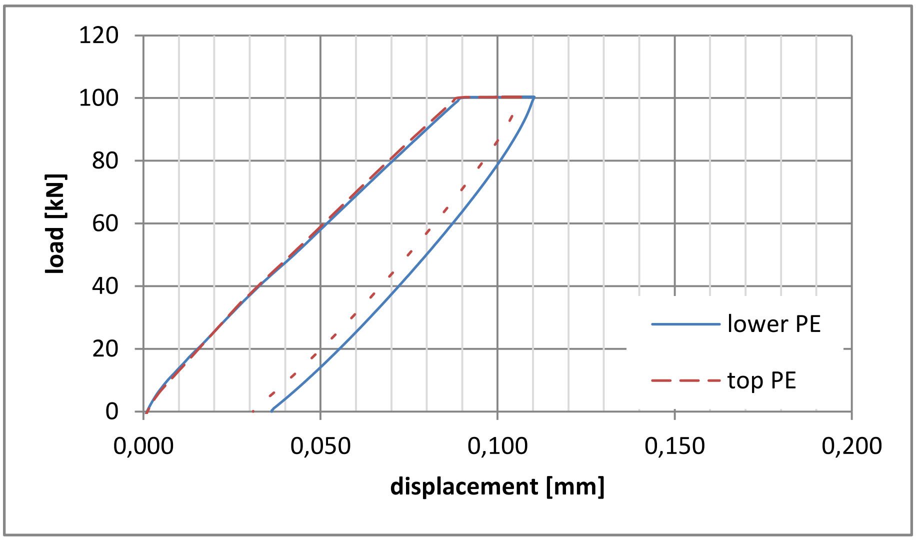

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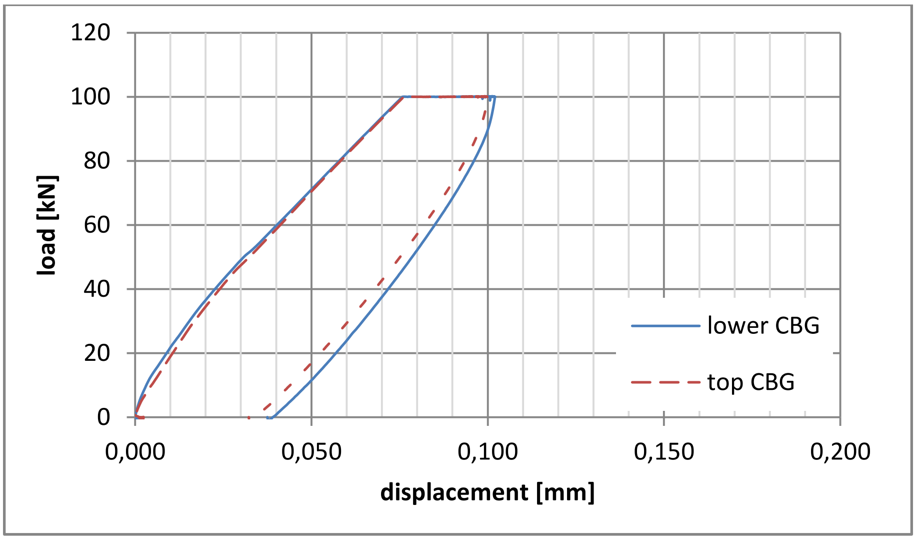

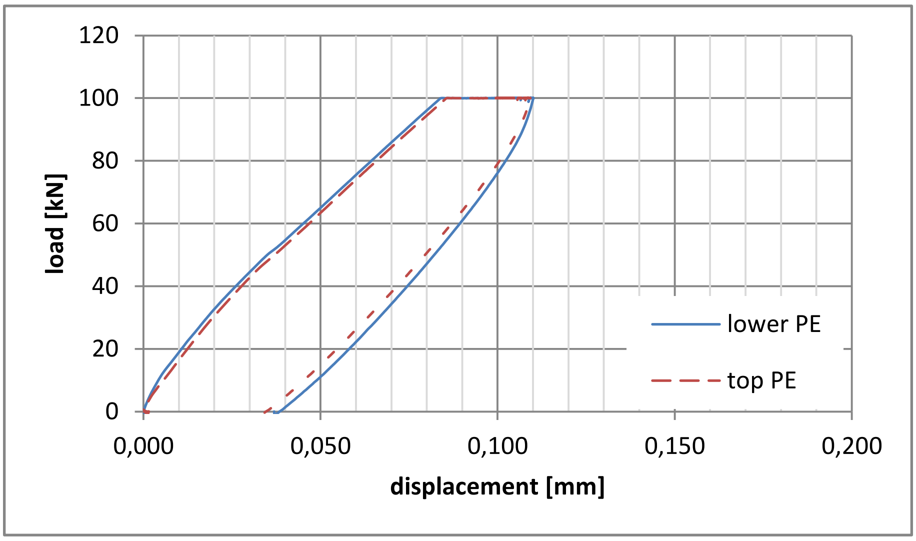

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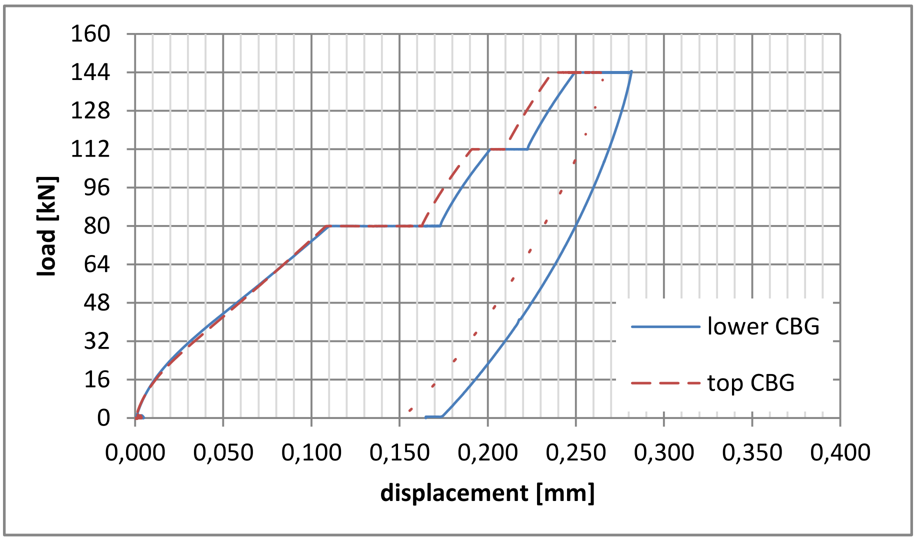

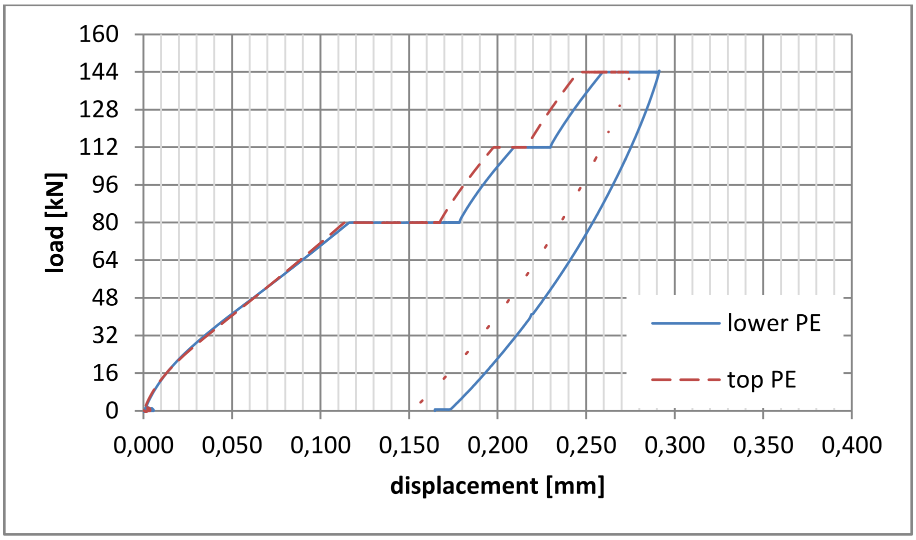

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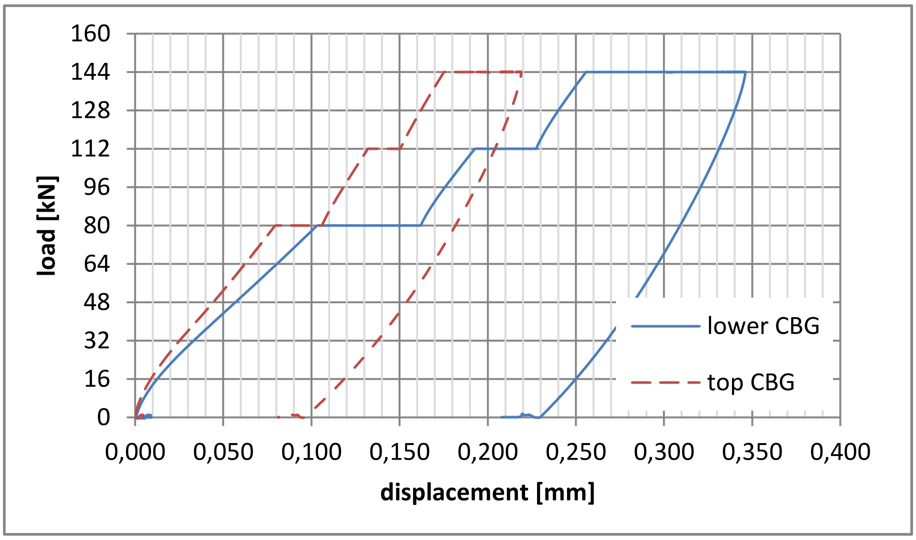

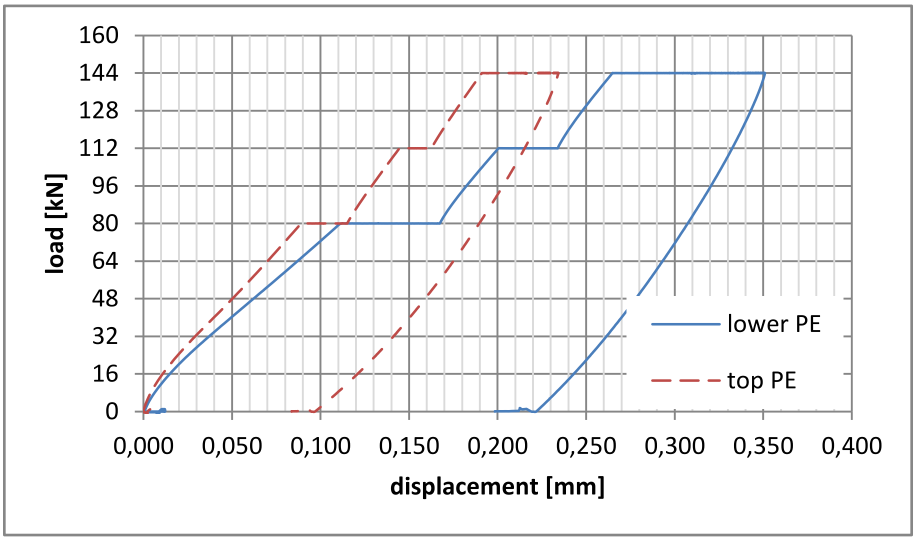

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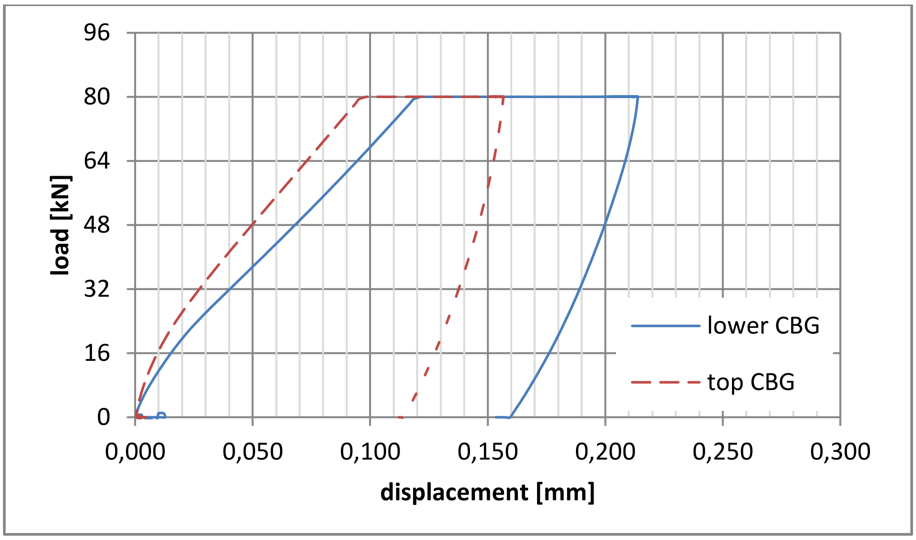
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displacement [mm]
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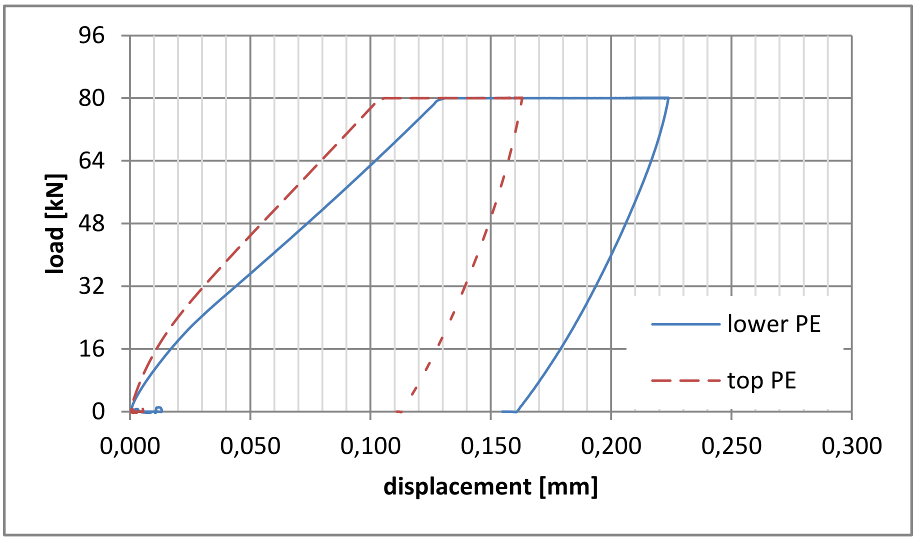
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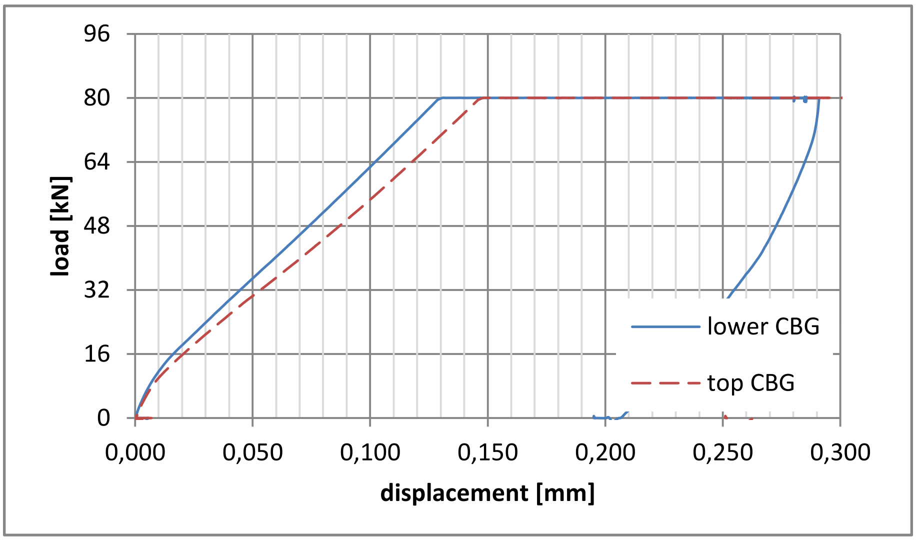
(i) R2K-06h-2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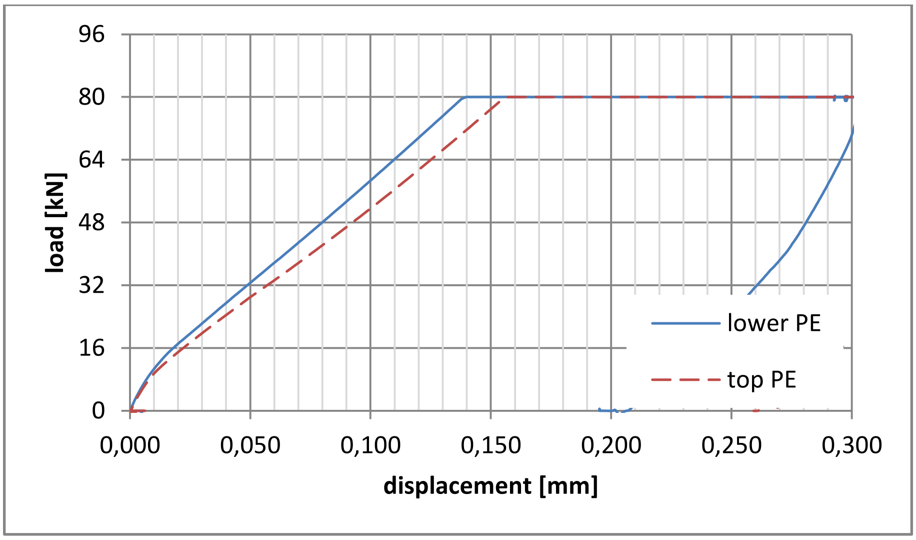

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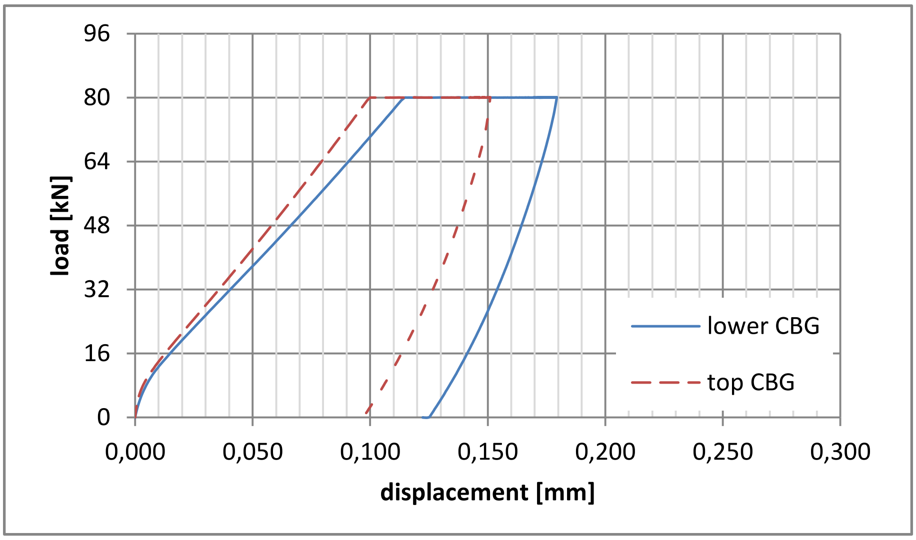

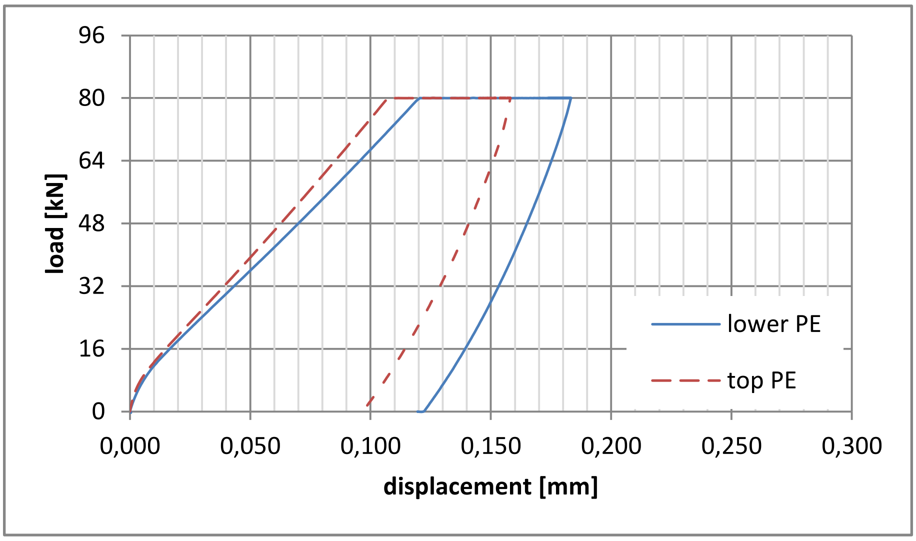

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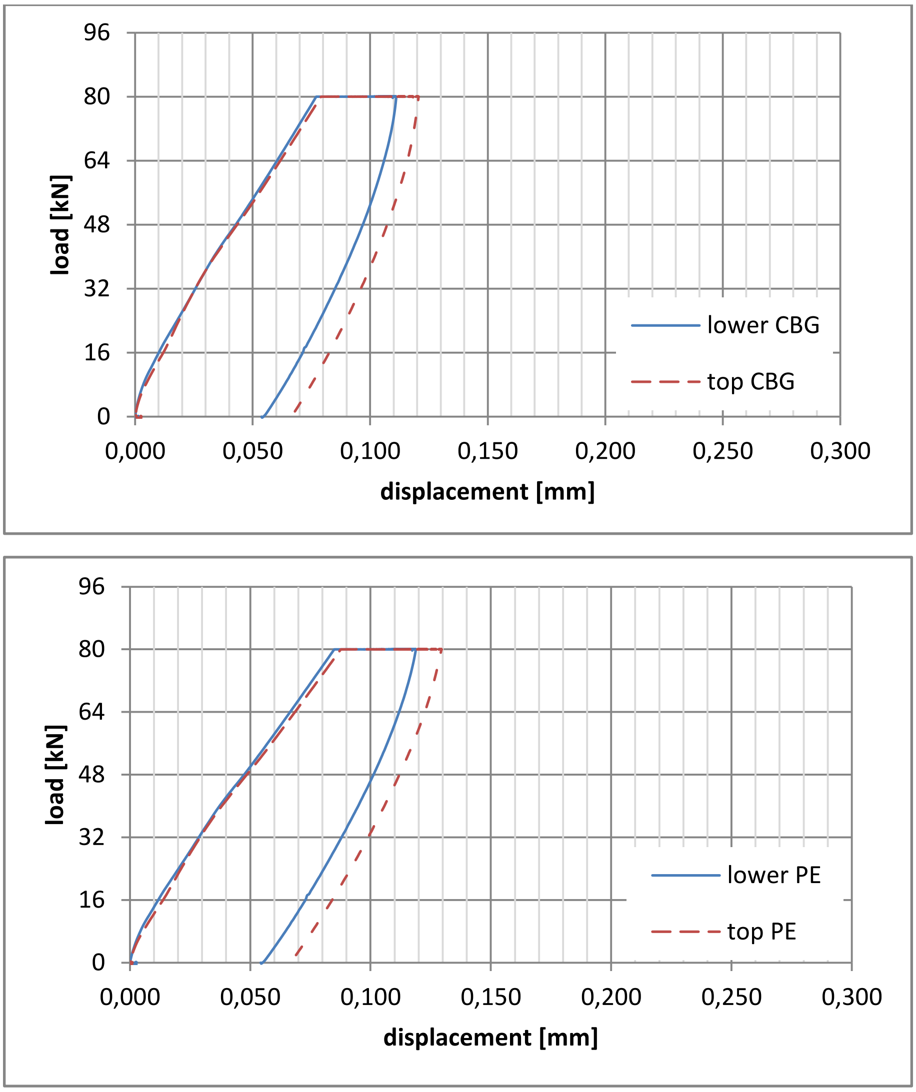
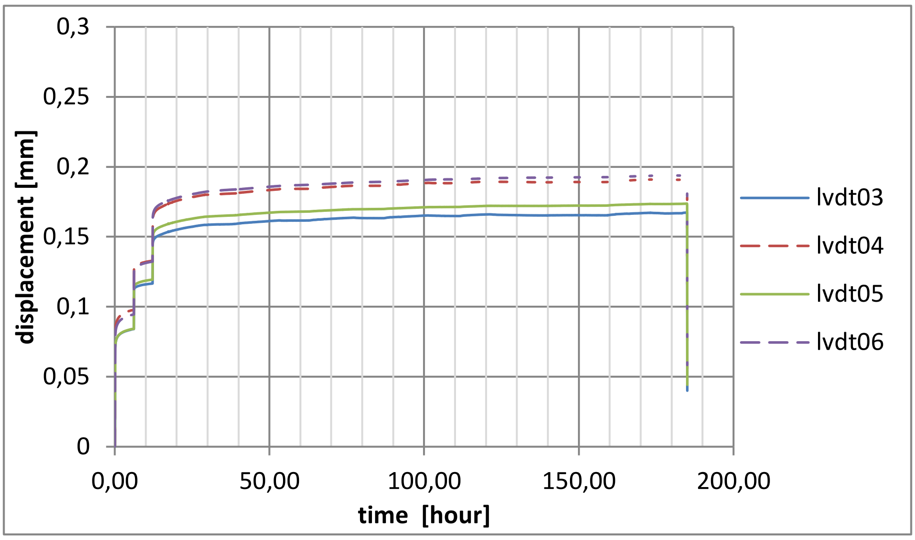
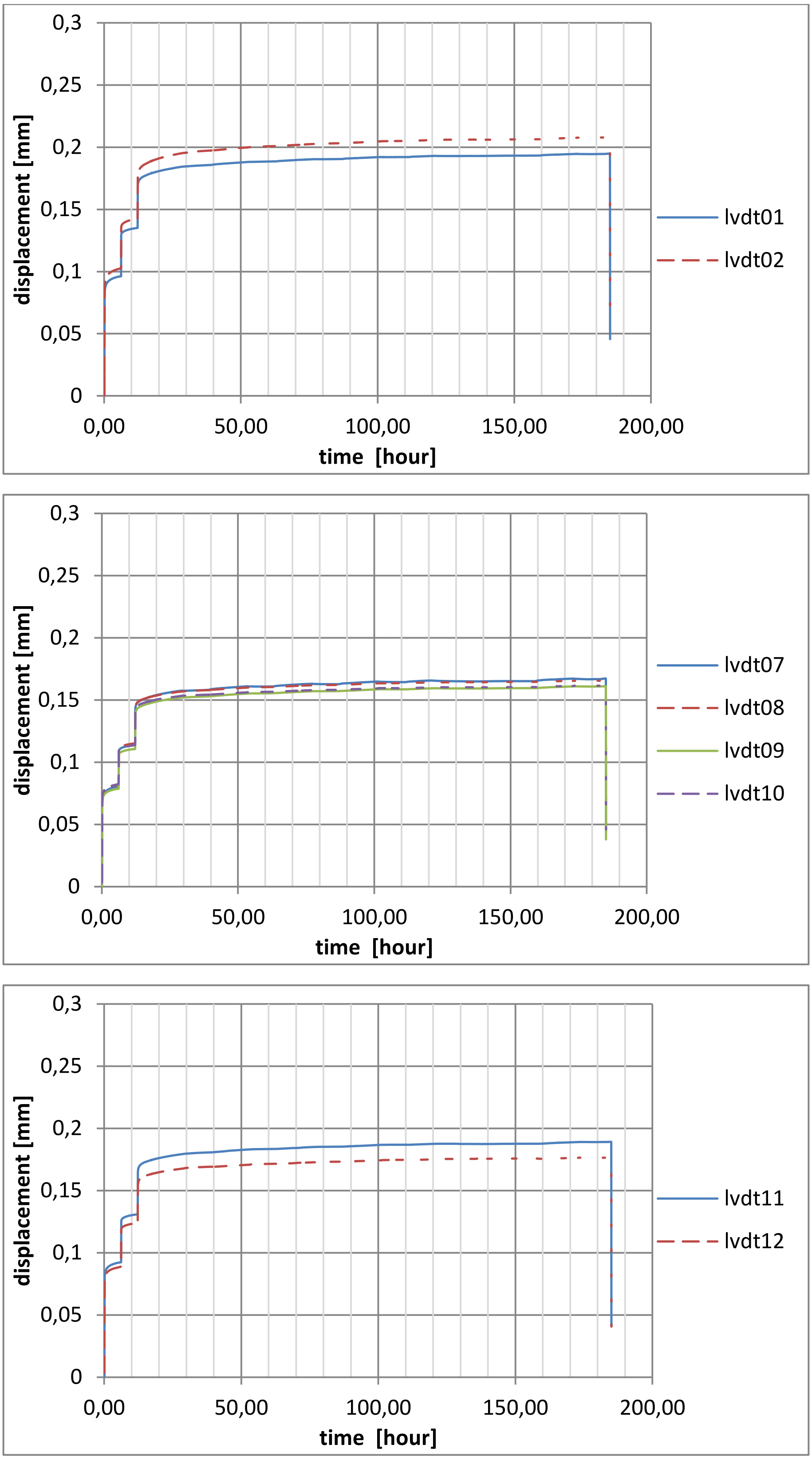


(l) R2K-24h-2a

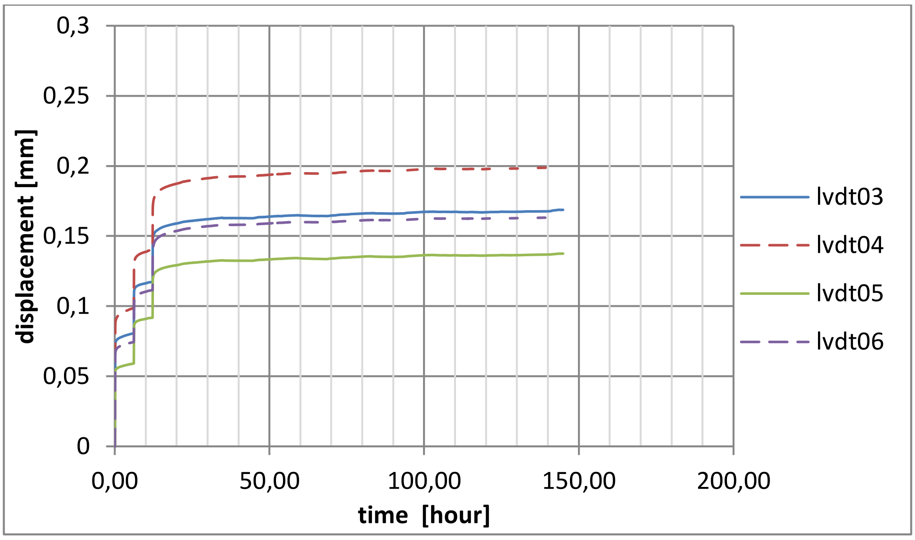
Figure 2.19: Load vs displacement curves of Stage 1 - Step 3

Secondly, The displacement-time curves of these 12 specimens are shown in Figure 2.20. The LVDTs location could be seen in Figure 2.6.





(a) Araldite-06h-1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time [hour]
lvdt03
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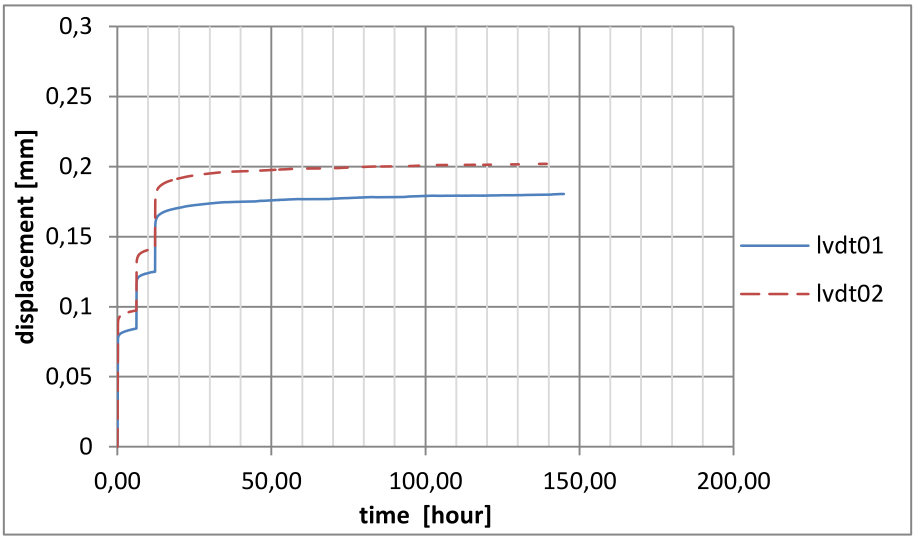
lvdt06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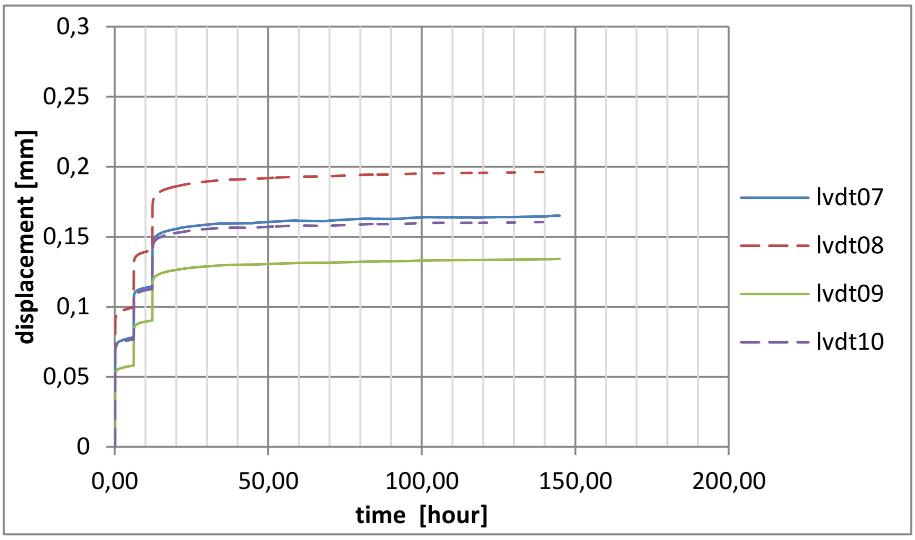
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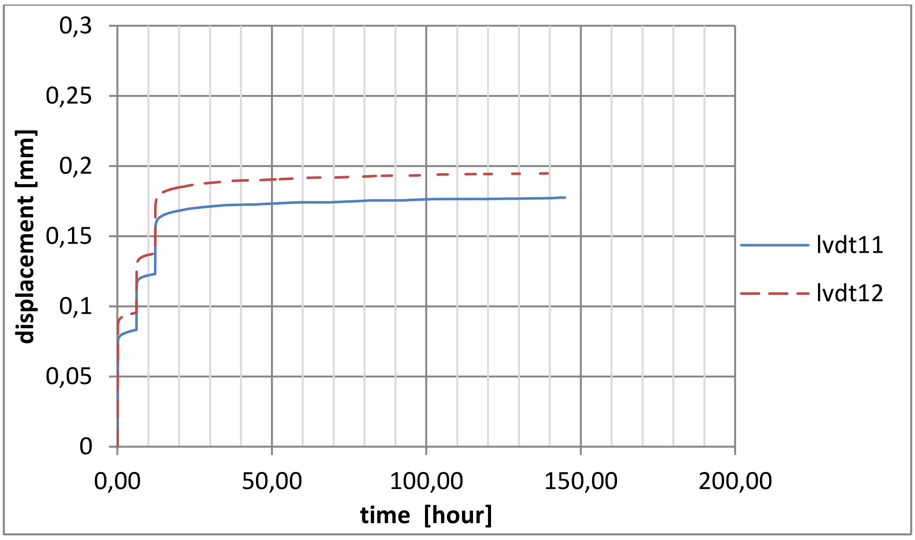

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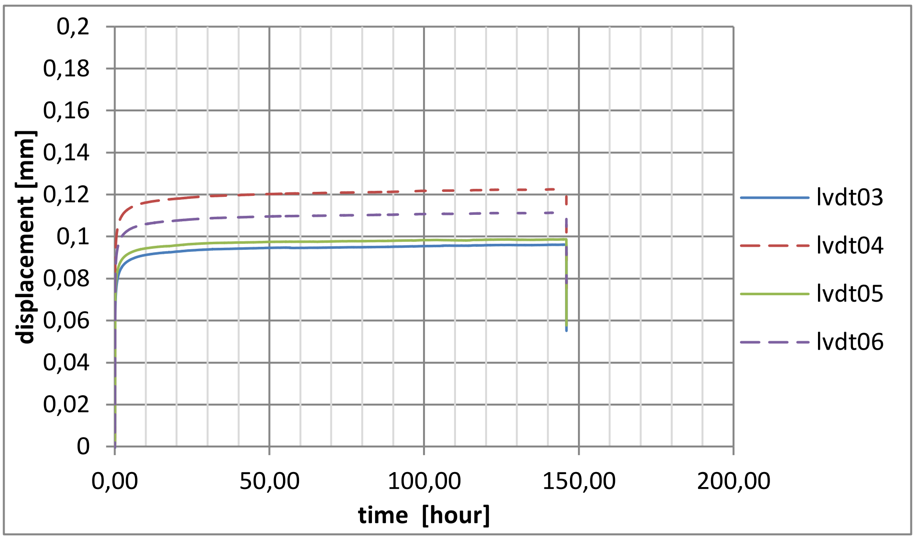
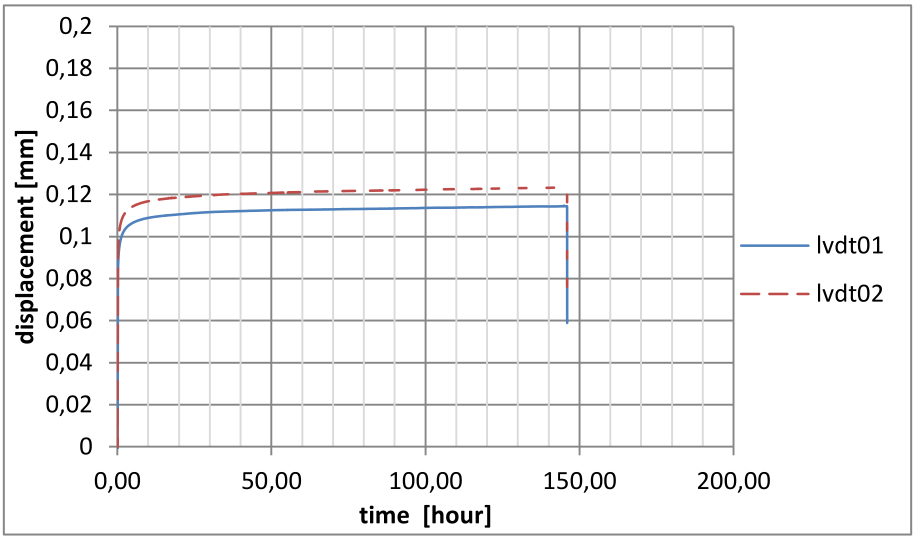
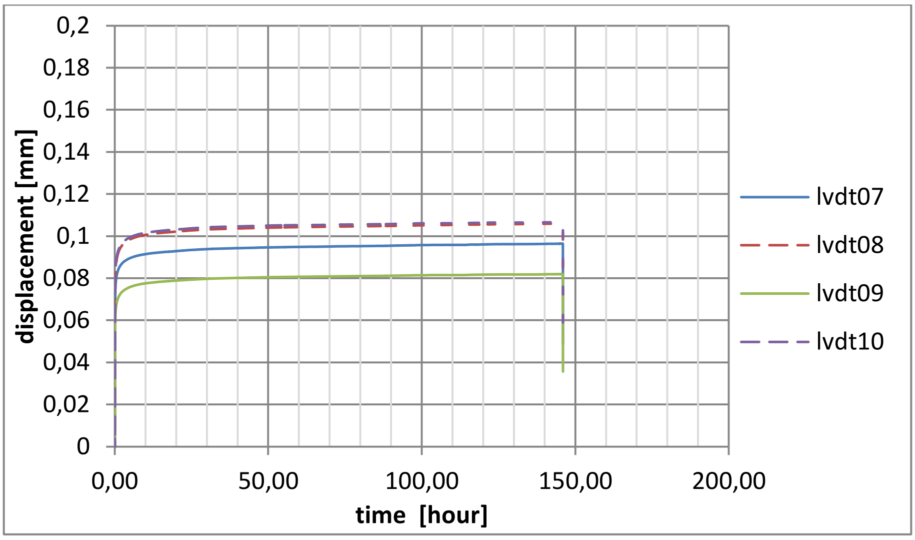
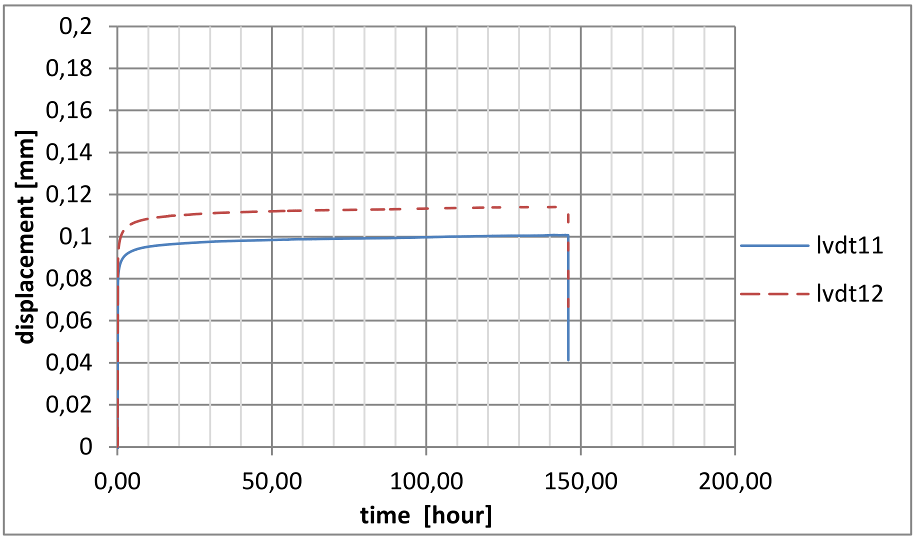
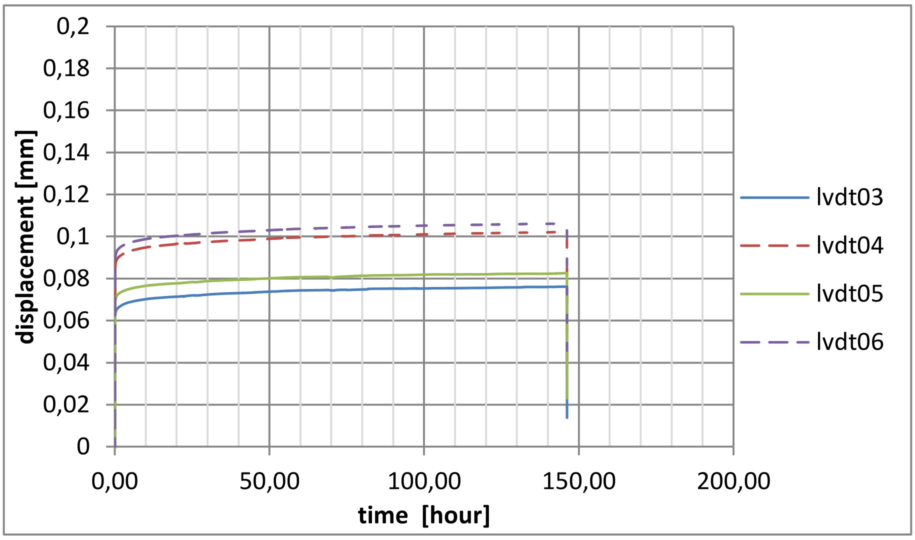


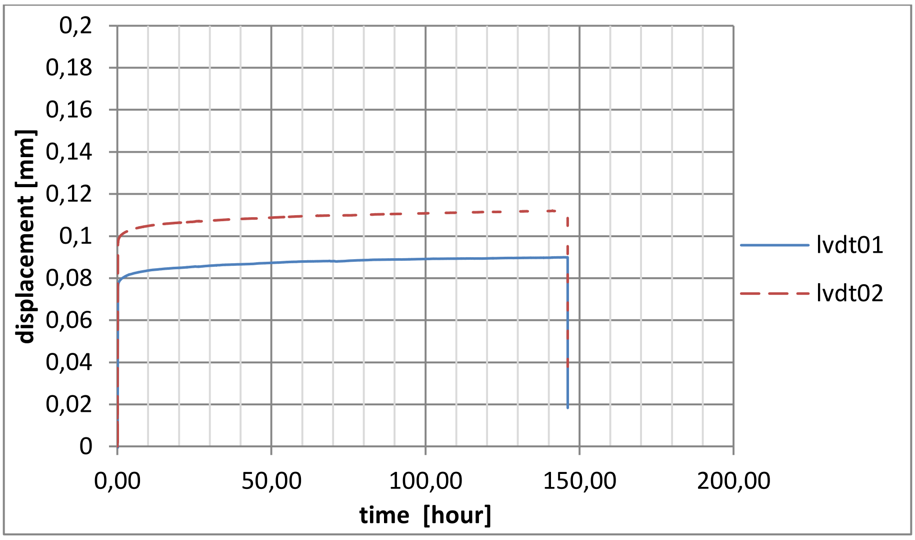


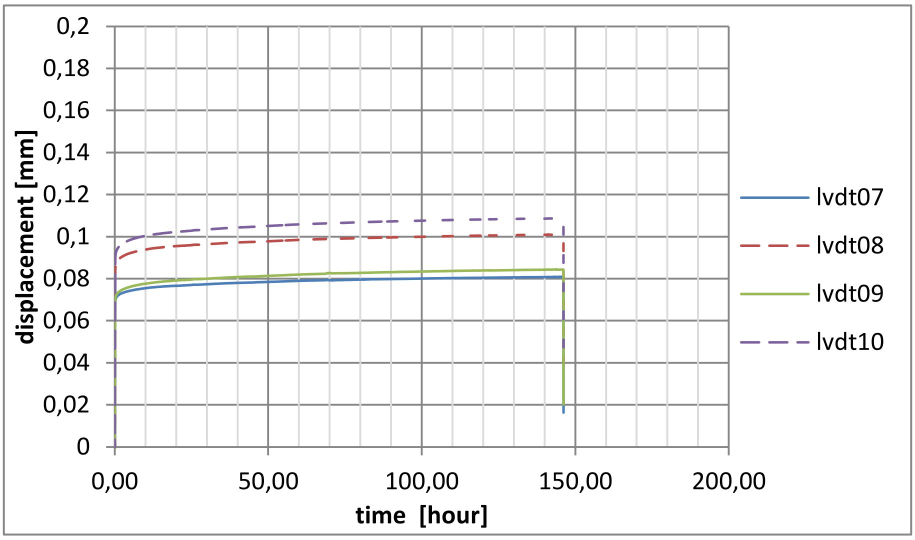


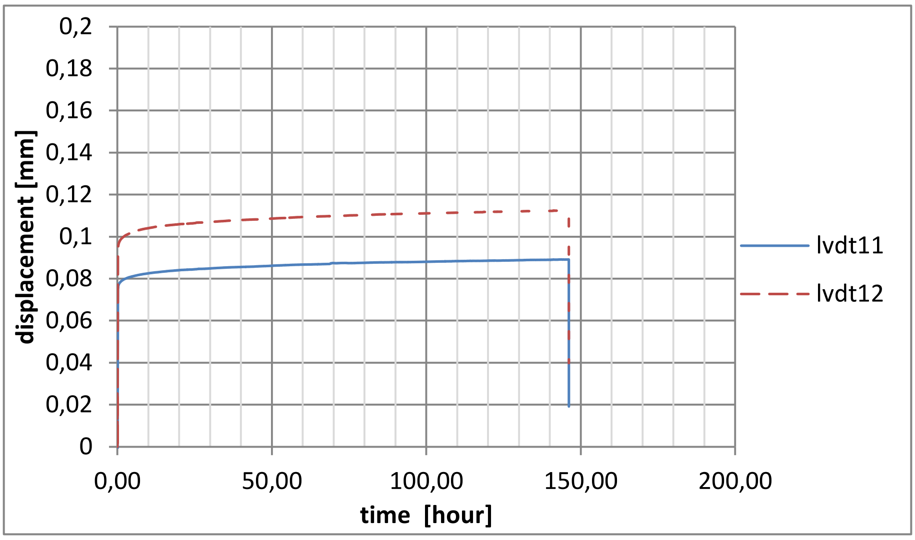


(c) Araldite-06h-2









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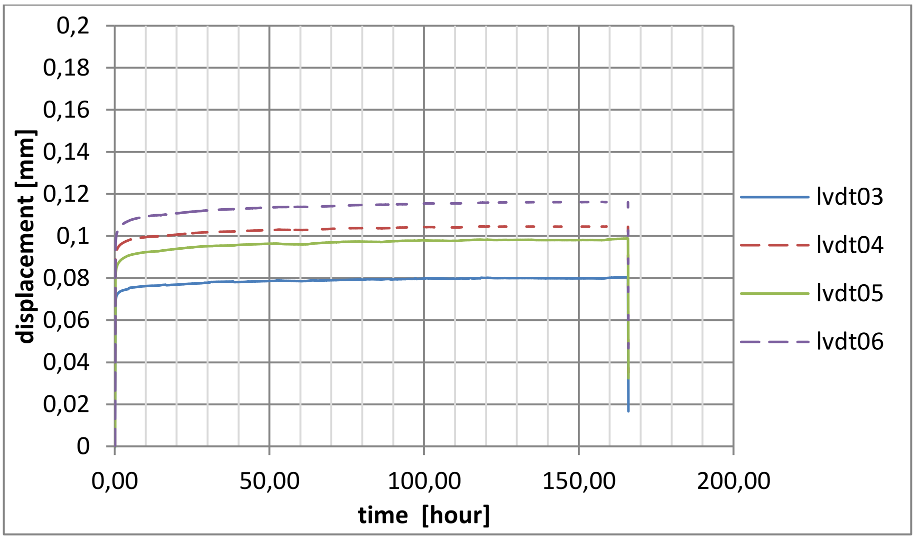

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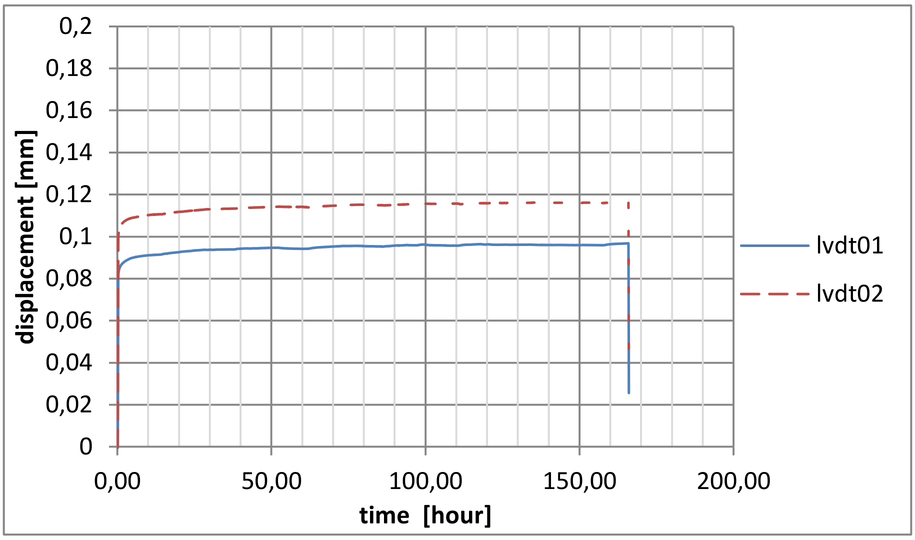

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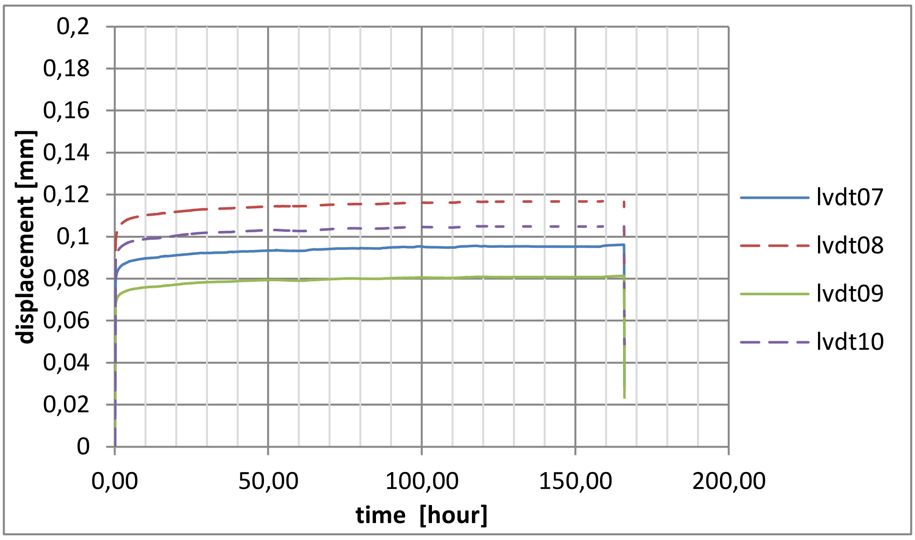

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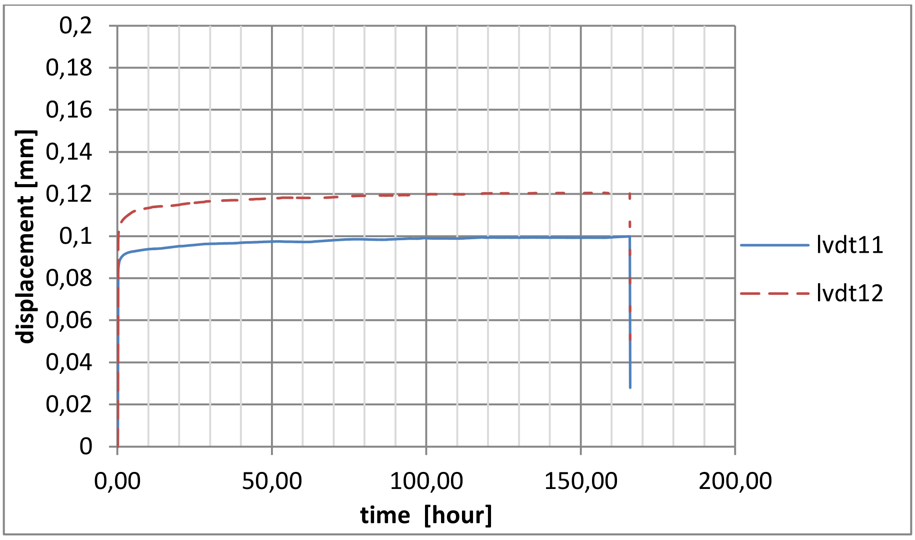

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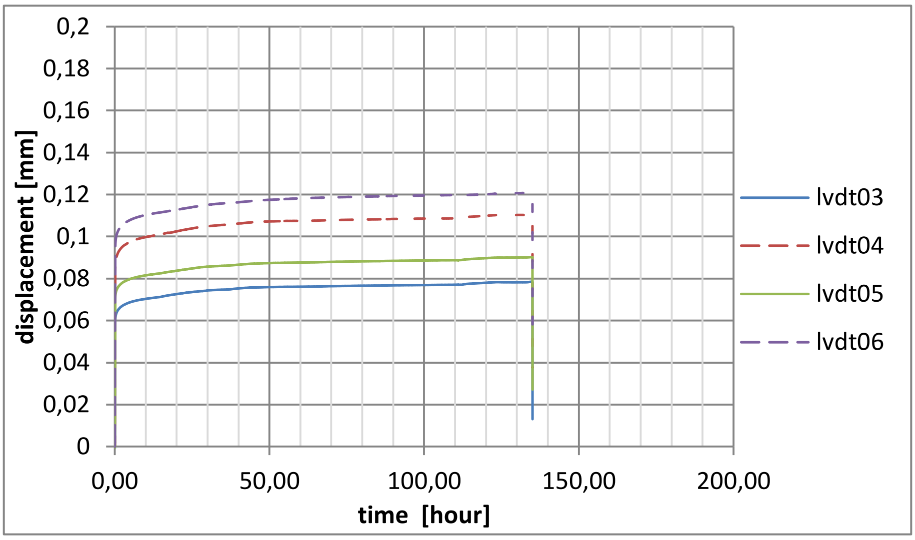

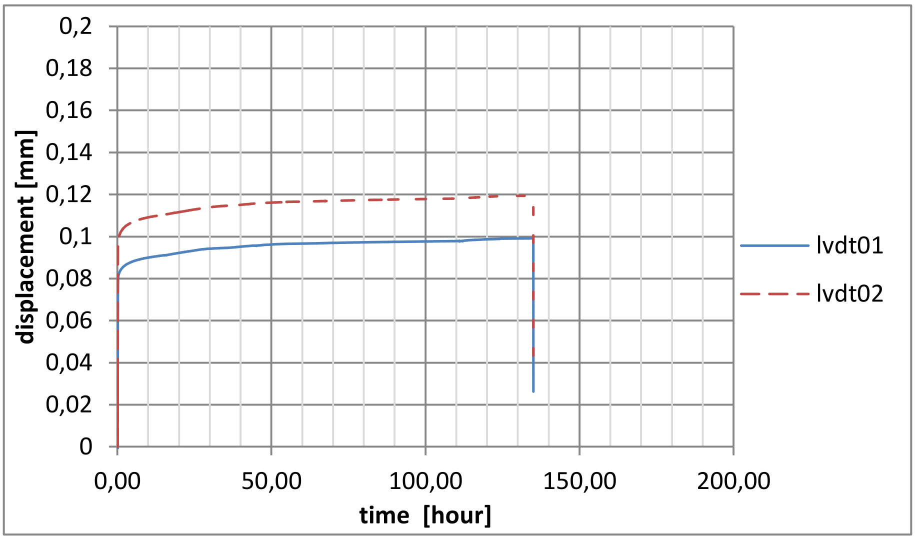

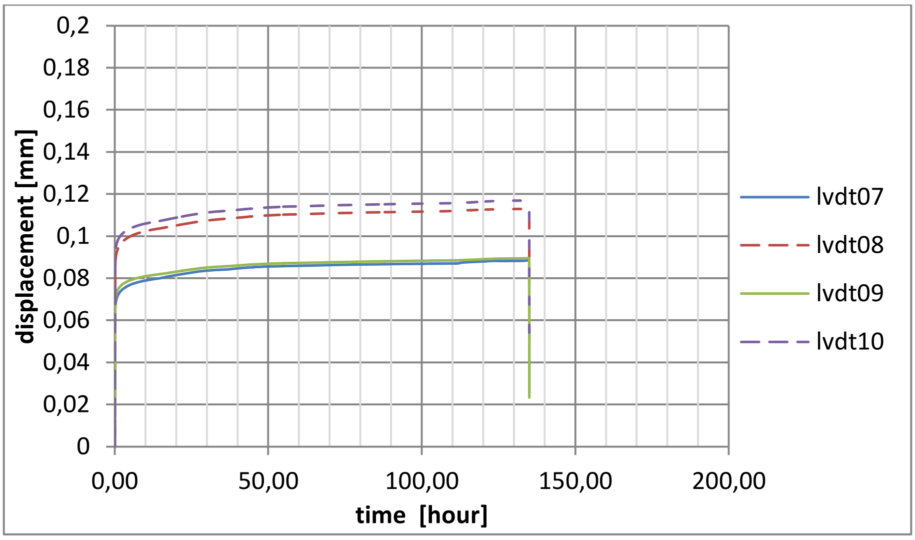

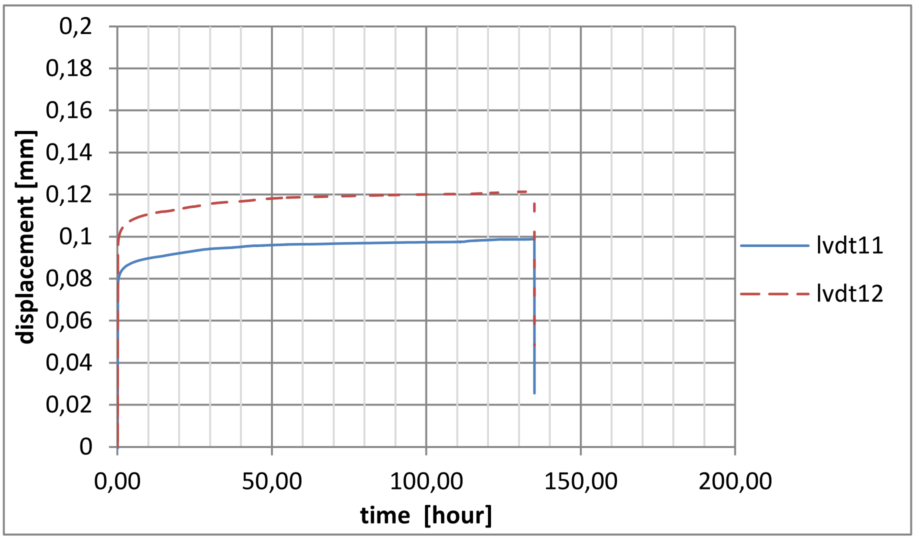

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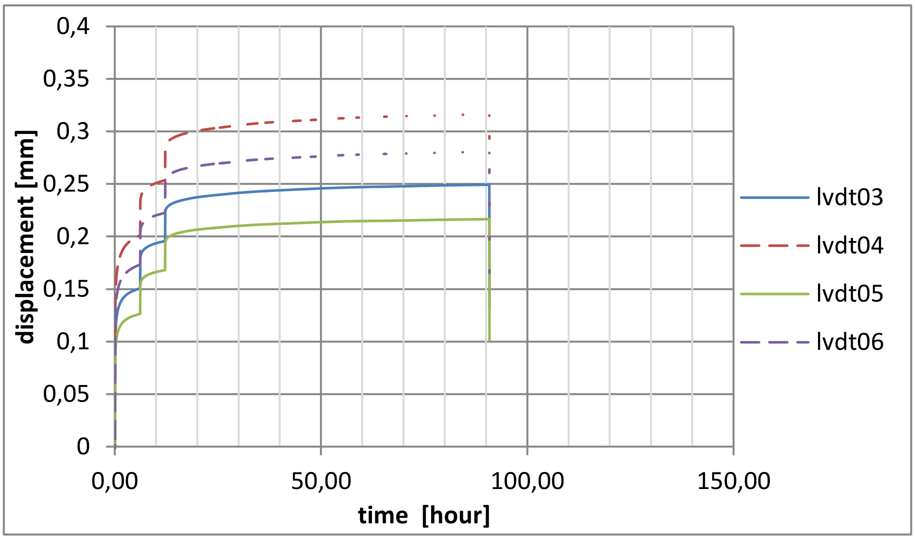

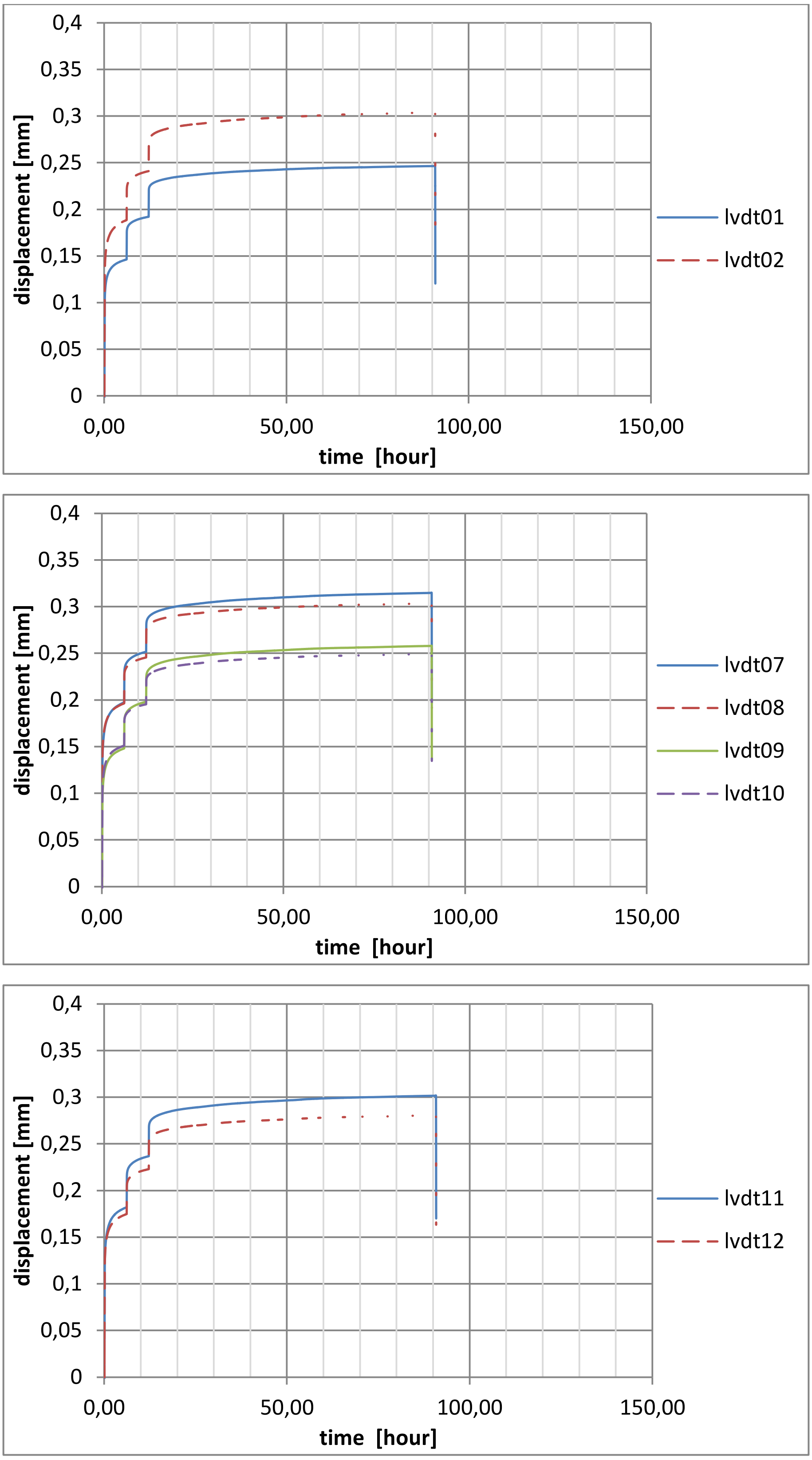
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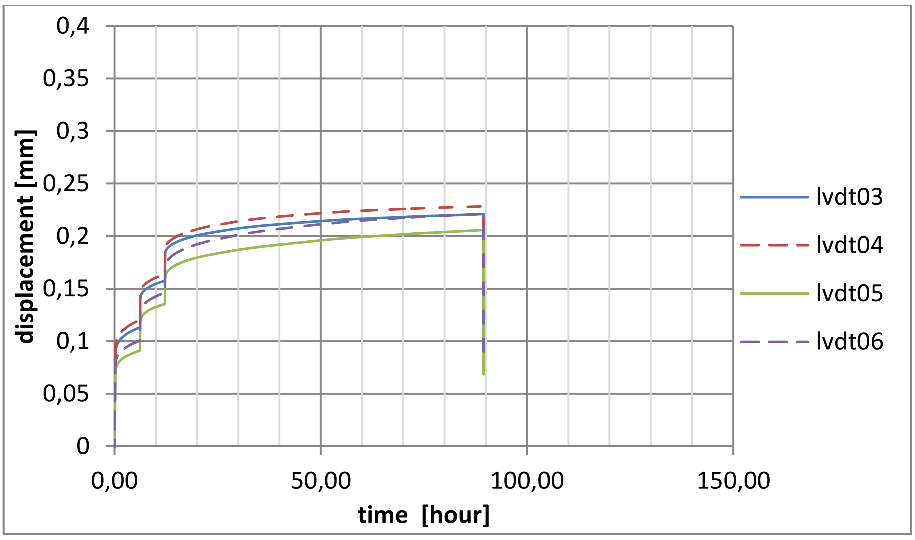
(g) R2K-06h-1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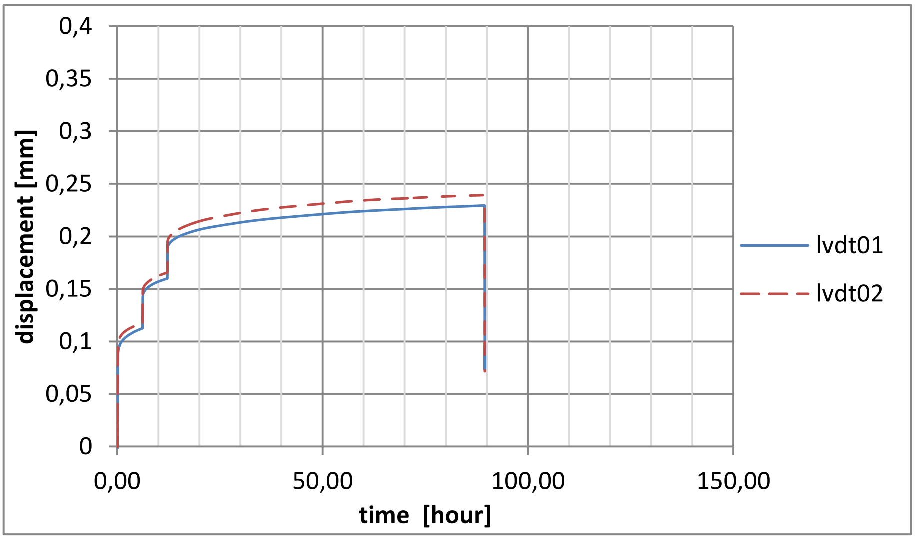
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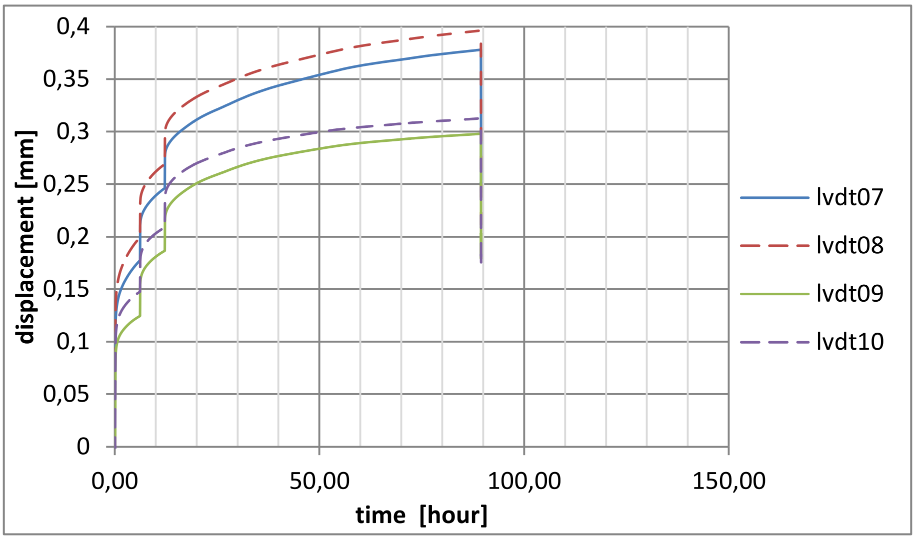
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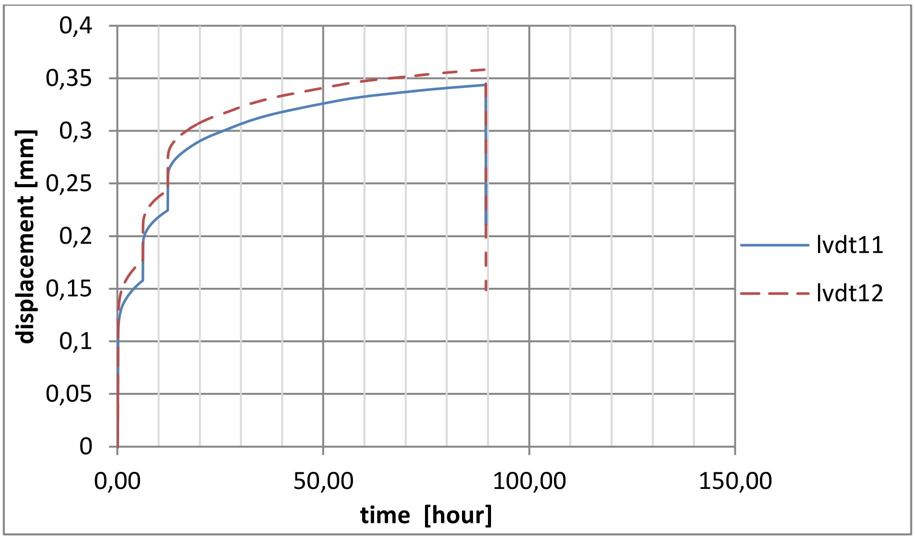
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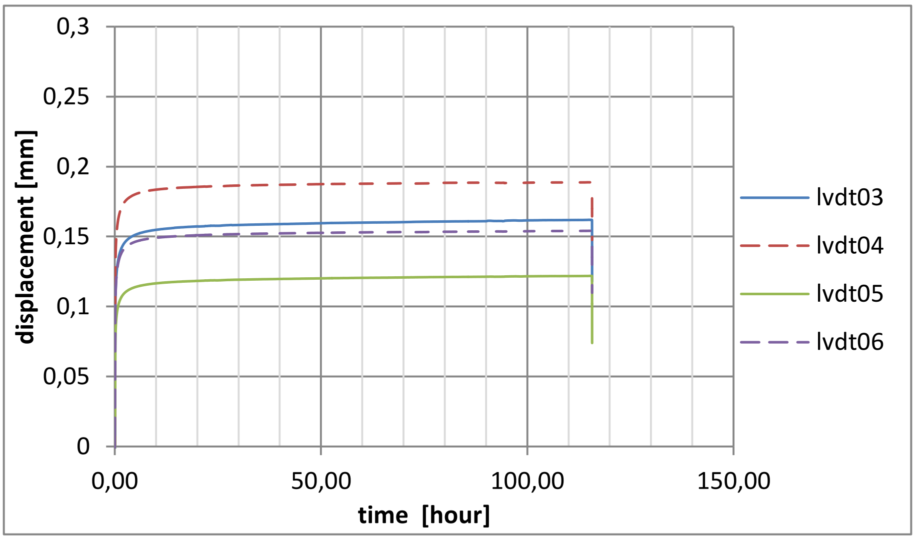
(h) R2K-24h-1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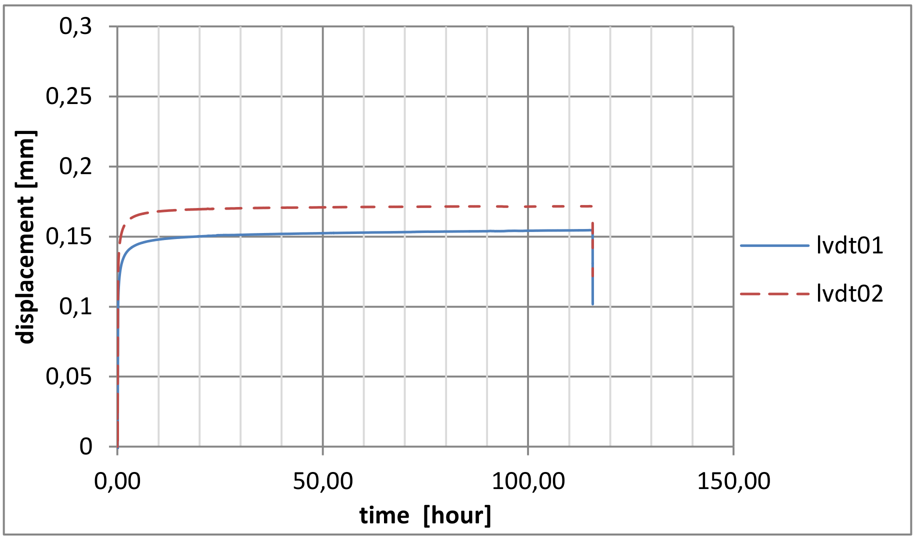
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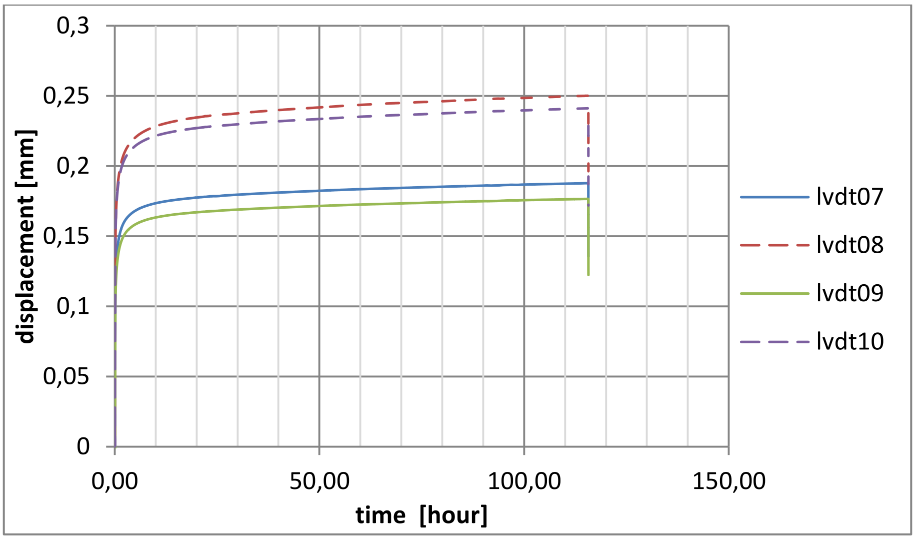
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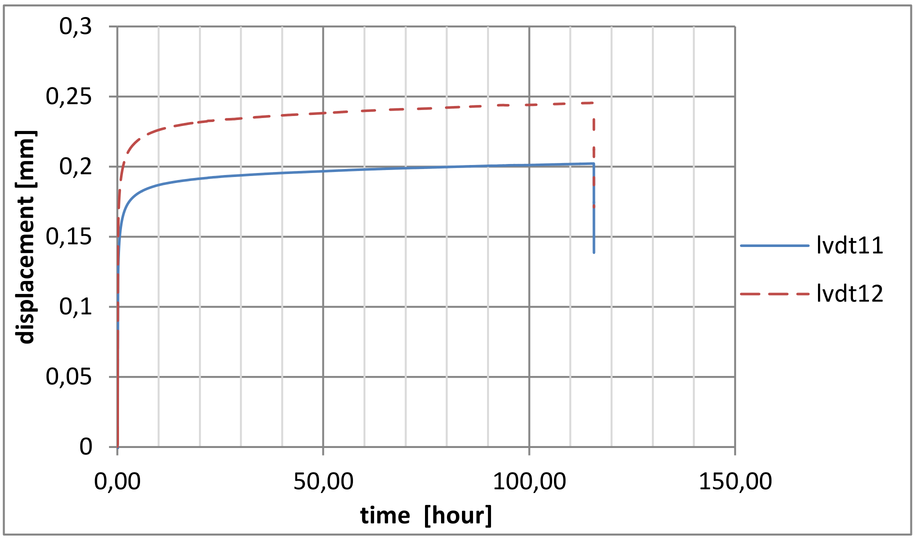
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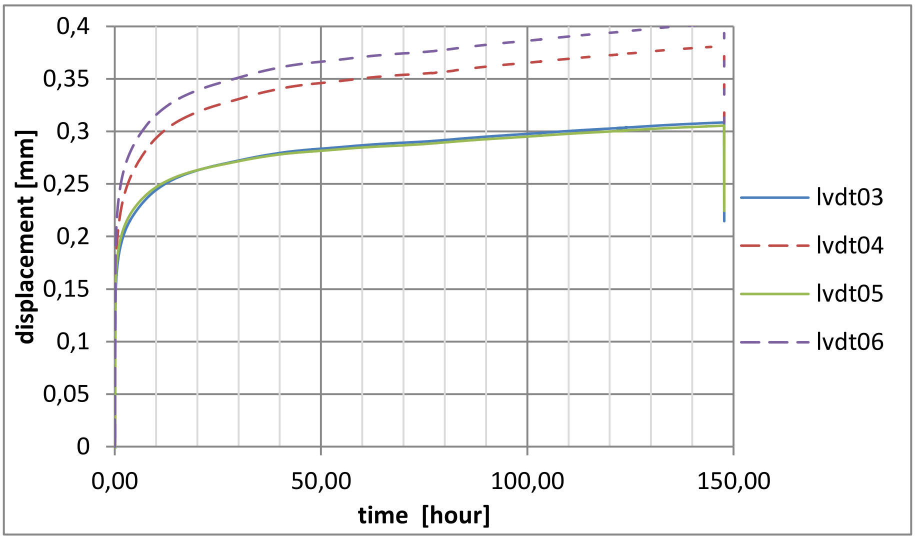
(i) R2K-06h-2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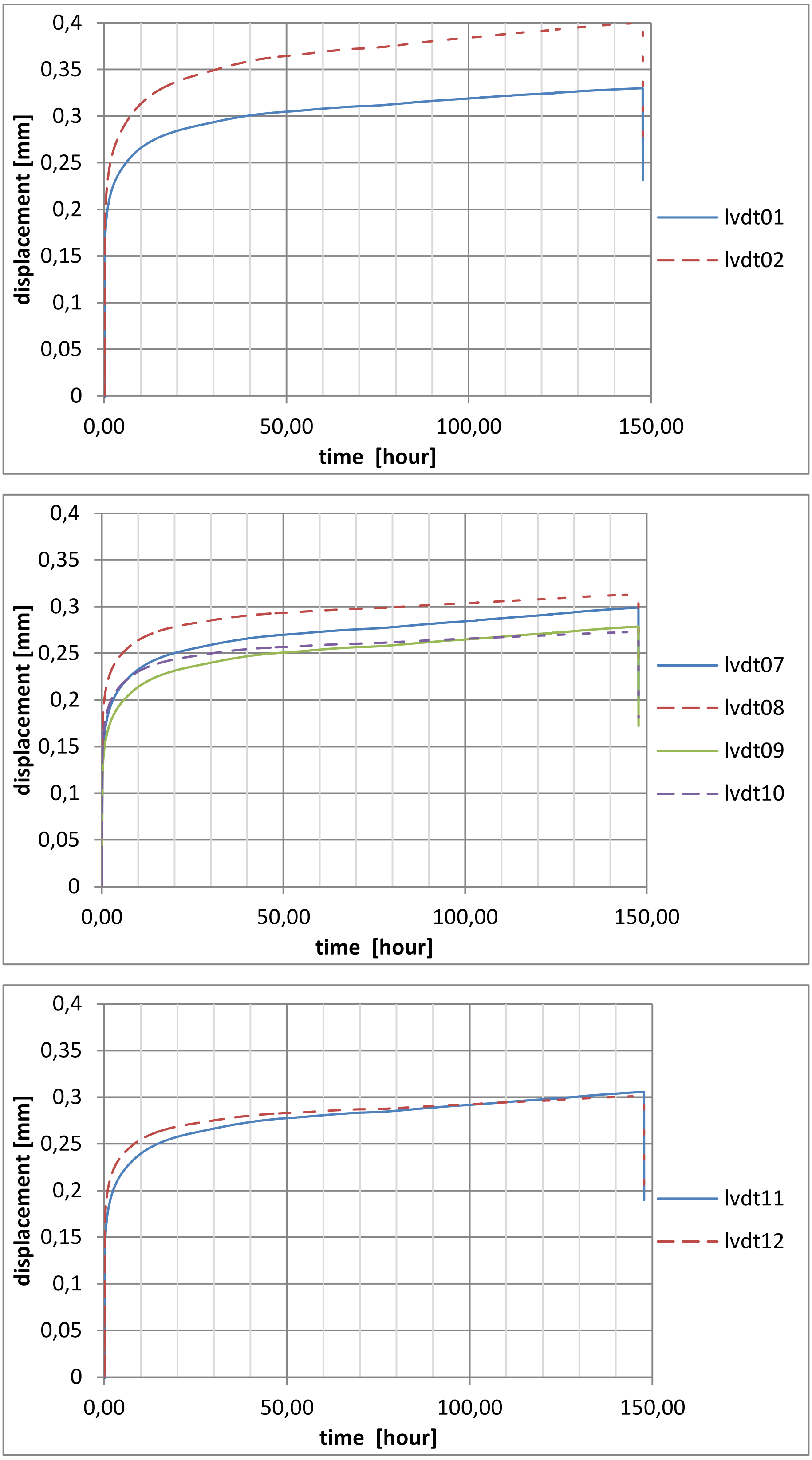
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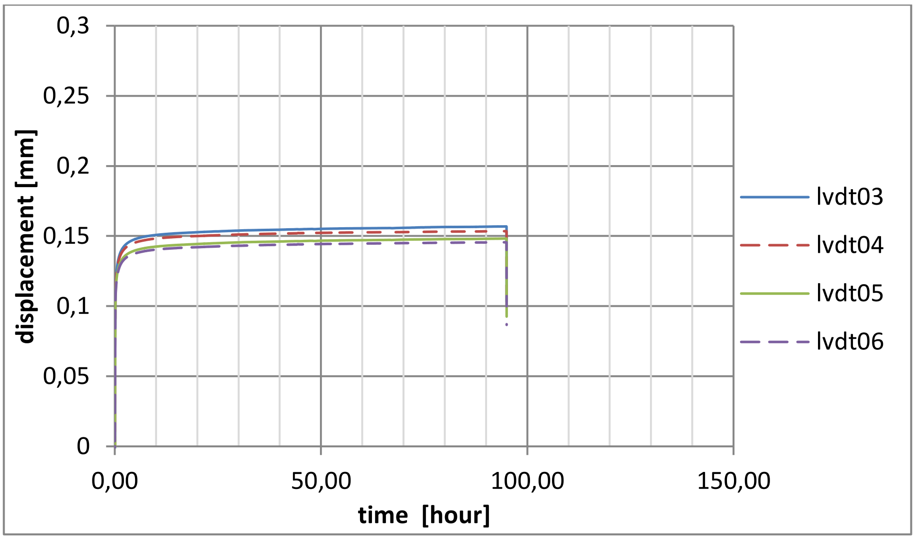
(j) R2K-24h-2



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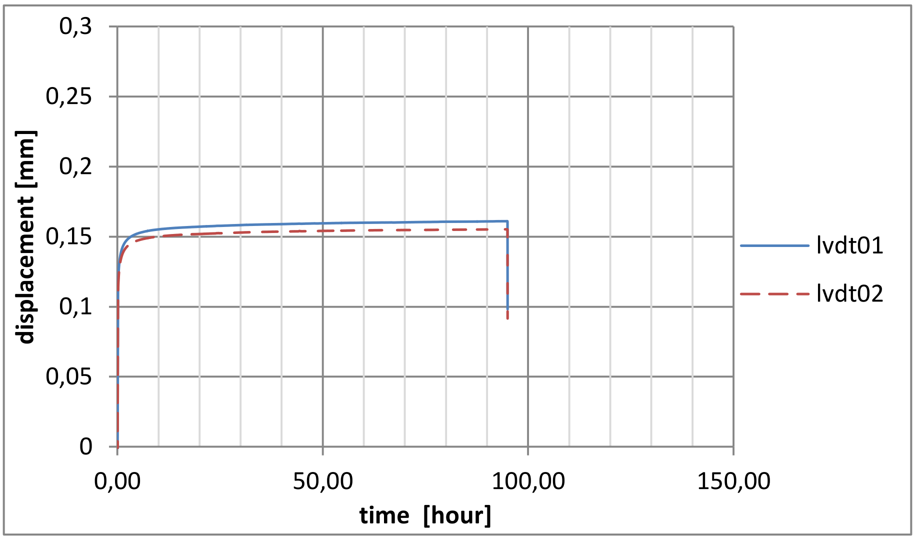

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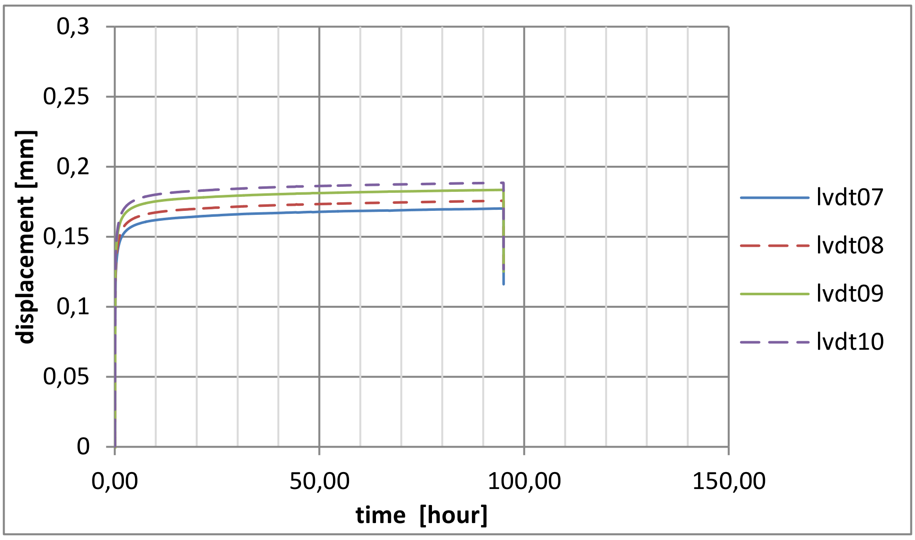
lvdt02



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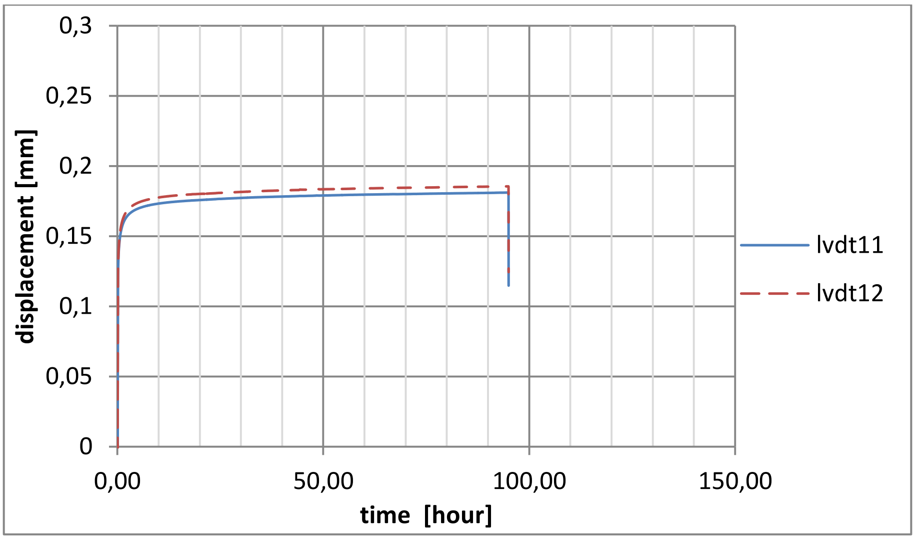
lvdt07
lvdt08
lvdt09
lvdt10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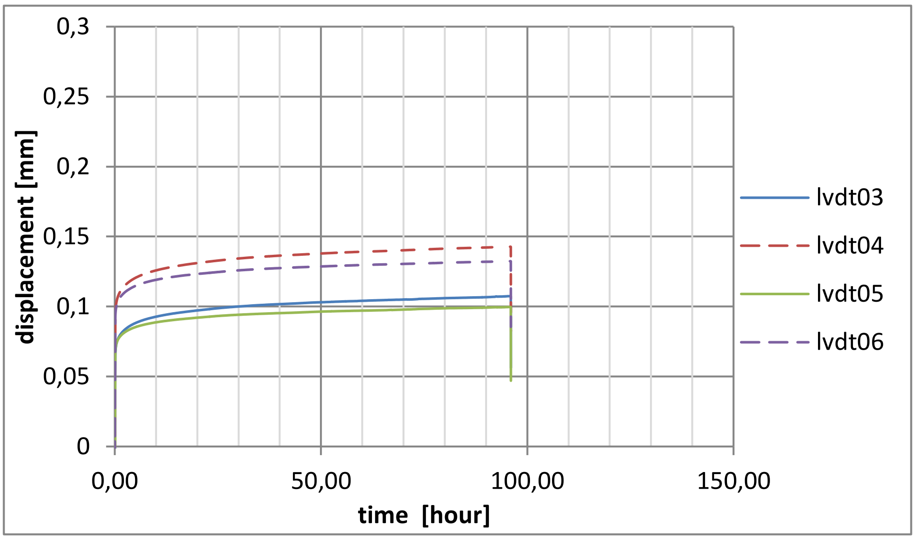
lvdt11
lvdt12

(k) R2K-06h-2a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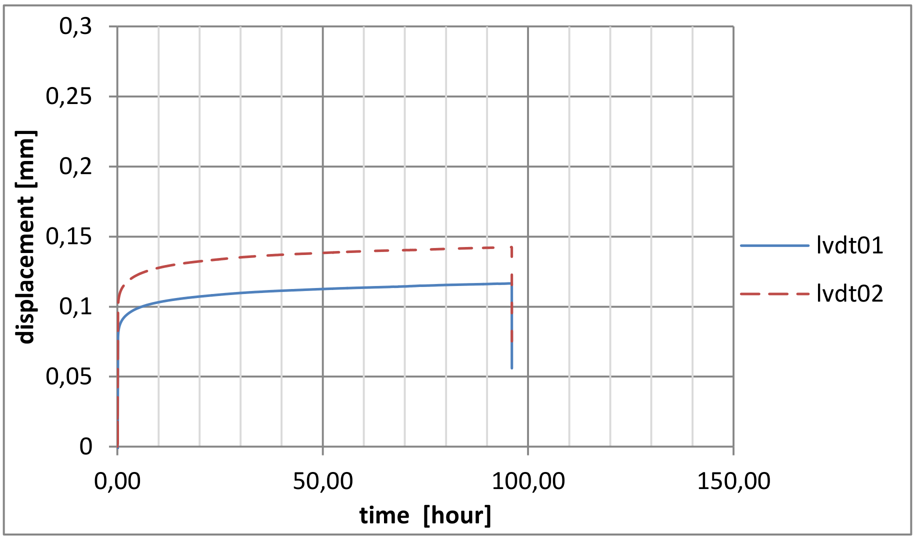
time [hour]
lvdt03
lvdt04
lvdt05
lvdt06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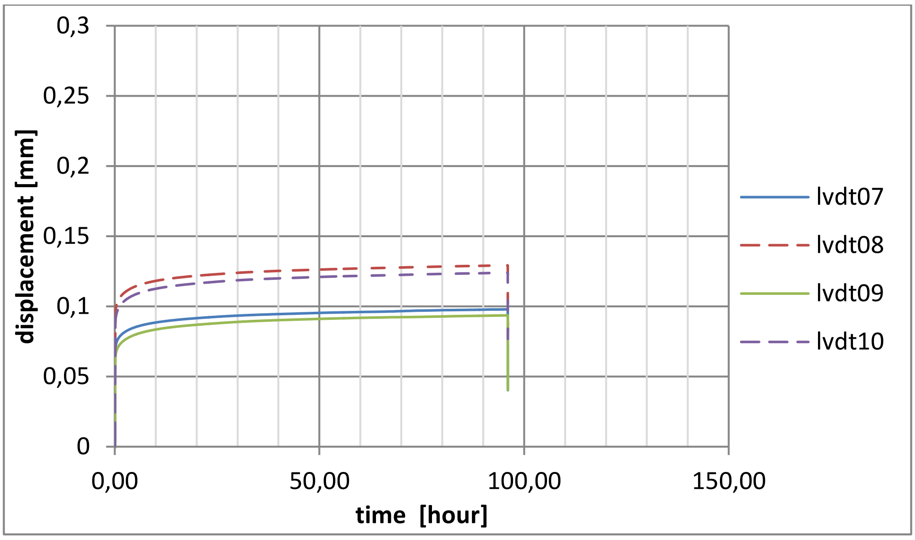
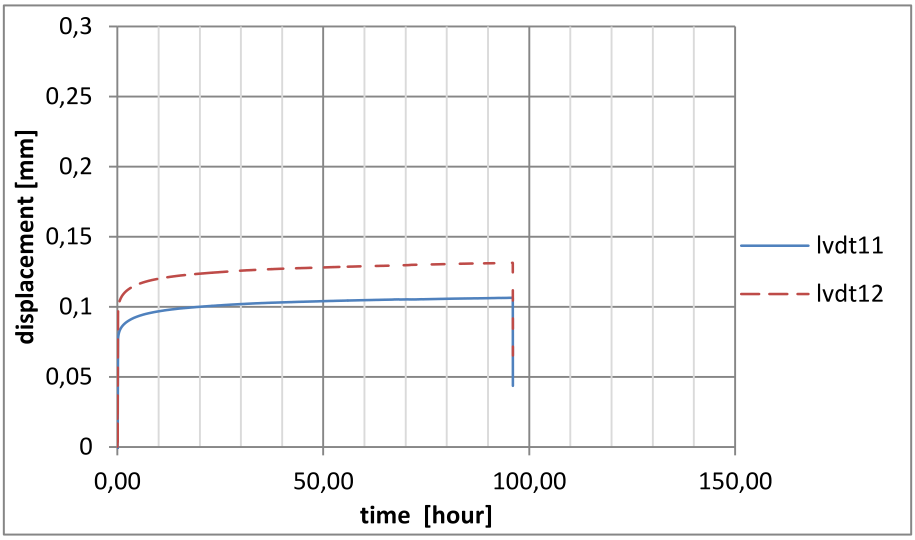
time [hour]
lvdt01
lvdt02





(l) R2K-24h-2a

Figure 2.20: Displacement vs time curves of Stage 1 - Step 3

2.2.2.3.6 Analyses

Based on the test results shown above, firstly we can get some initial impression about the resin's bearing capacity and creep behaviour, simply listed as below.

- Resin Araldite shows up a stable bearing capacity both under the step load and under the constant load, the force-displacement curves look like having little disperse between specimens of 6 hours curing time and 24 hours curing time. With the increase of loading time, the growth rate of the displacement gradually slow down. After 90 hours loading, all of the displacement-time curves tend to be parallel to the horizontal axis. The connection's creep behaviour seems slightly.
- The bearing capacity of Resin Edilon Dex-R2K has great disperse between different specimens and even between different connections of the identical specimen, for example, the specimen R2K-24-1. The connection's creep behaviour appears significant in general, especially for specimen R2K-24h-1 and specimen R2K-24h-2. It is difficult to sum up the regularity of the bearing capacity and creep behaviour influenced by curing time.

- In terms of visual, due to the great variability in bearing capacity and creep performance, resin Edilon Dex-R2K seems difficult to become a qualified candidate resin which can take the place of resin Araldite.

These text is only a simple and intuitive summary, further analysis must depend on the comparison from specific figures.

(1) Araldite

Because the varieties of load type and duration, comparison of the displacements must only be made on the same load conditions.

Firstly, based on the displacement-time curves in Figure 2.20, displacements at some selected critical time points are listed in Table 2.11 for specimens under step load. Taking into account the similarity of the results, only the displacements at LVDT 01/02/11/12 are listed and calculated.

The selection principle of critical time points in Table 2.11 are:

- The first point in time when the load reaches the step preset value, that is 100 kN, 140 kN, and 180 kN. So these three time points are determined by the force value actually
- The time of loading reaches to 90 hours, which is the minimum loading time at the initial experimental plan
- The time of loading reaches to 145 hours, which is the shorter one on loading time of these two specimens in practice

Table 2.11: Displacement at critical time points (Araldite - Step Load)

Name of specimen	Time point (hours)	Force value (kN)	Displacement (mm)					Normalization	Difference (%)
			Lvdt 01	Lvdt 02	Lvdt 11	Lvdt 12	Avg. of 4 Lvdt		
Araldite-06h-1	0.1	100	0.081	0.085	0.080	0.076	**0.081**	1	0
	6	140	0.129	0.135	0.124	0.118	**0.127**	1	0
	12	180	0.168	0.175	0.164	0.153	**0.165**	1	0
	90	180	0.191	0.204	0.186	0.173	**0.189**	1	0
	145	180	0.193	0.206	0.188	0.176	**0.191**	1	0
Araldite-24h-1	0.1	100	0.078	0.089	0.076	0.088	**0.083**	1.028	+2.8
	6	140	0.116	0.130	0.114	0.127	**0.122**	0.962	-3.8
	12	180	0.157	0.174	0.154	0.170	**0.164**	0.992	-0.8
	90	180	0.178	0.200	0.175	0.193	**0.187**	0.989	-1.1
	145	180	0.180	0.202	0.177	0.195	**0.189**	0.988	-1.2

Note: The normalization values and difference are all based on the first specimen.

From the calculation results in Table 2.11, we can find that these two specimens have almost the same displacement values at five selected critical time points. The maximum difference is only -3.8 % at time point of 6 hours. By comparing the displacement-time curves of these two specimens in Figure 2.20, we can find that their displacement-time curves are almost coincidence.

It can be clearly demonstrated that the curing time did not affect the mechanical behaviour of these two specimens.

Secondly, based on the displacement-time curves in Figure 2.20, displacements at some selected critical time points are listed in Table 2.12 for specimens under constant load. Taking into account the similarity of the results, only the displacements at LVDT 01/02/11/12 are listed and calculated.

The selection principle of critical time points in Table 2.12 are:

- The first point in time when the load reaches the preset value, that is 100 kN
- The time of loading reaches to 90 hours
- The time of loading reaches to 135 hours, which is the shortest load time of the four specimens in practice

Table 2.12: Displacement at critical time points (Araldite - Constant Load)

Name of specimen	Time point (hours)	Force value (kN)	Displacement (mm)					Normalization	Difference (%)
			Lvdt 01	Lvdt 02	Lvdt 11	Lvdt 12	Avg. of 4 Lvdt		
Araldite-06h-2	0.1	100	0.080	0.088	0.077	0.086	**0.083**	1	0
	90	100	0.113	0.122	0.099	0.113	**0.112**	1	0
	135	100	0.114	0.123	0.101	0.114	**0.113**	1	0
Araldite-24h-2	0.1	100	0.078	0.099	0.077	0.097	**0.088**	1.060	+6.0
	90	100	0.089	0.110	0.088	0.111	**0.100**	0.890	-11.0
	135	100	0.090	0.112	0.089	0.112	**0.101**	0.892	-10.8
Araldite-06h-2a	0.1	100	0.082	0.100	0.084	0.100	**0.092**	1.106	+10.6
	90	100	0.096	0.115	0.099	0.119	**0.107**	0.960	-4.0
	135	100	0.096	0.116	0.099	0.120	**0.108**	0.954	-4.6
Araldite-24h-2a	0.1	100	0.078	0.094	0.076	0.093	**0.085**	1.030	+3.0
	90	100	0.097	0.118	0.097	0.120	**0.108**	0.966	-3.4
	135	100	0.099	0.120	0.099	0.121	**0.110**	0.971	-2.9

Note: The normalization values and difference are all based on the first specimen.

From the calculation results in Table 2.12, we can find that maximum difference between Araldite-06h-2 and Araldite-06h-2a is +10.6 %, these two specimens have the same cuing time, that is 6 hours. The maximum difference between Araldite-06h-2 and Araldite-24h-2 is -11.0 %, these two specimens have the different cuing time. The maximum difference value looks similar. For further comparing the differences between these fours specimens, the average displacements of 4 Lvdts at three critical loading time points also could be drawn with a histogram, which is shown in Figure 2.21.

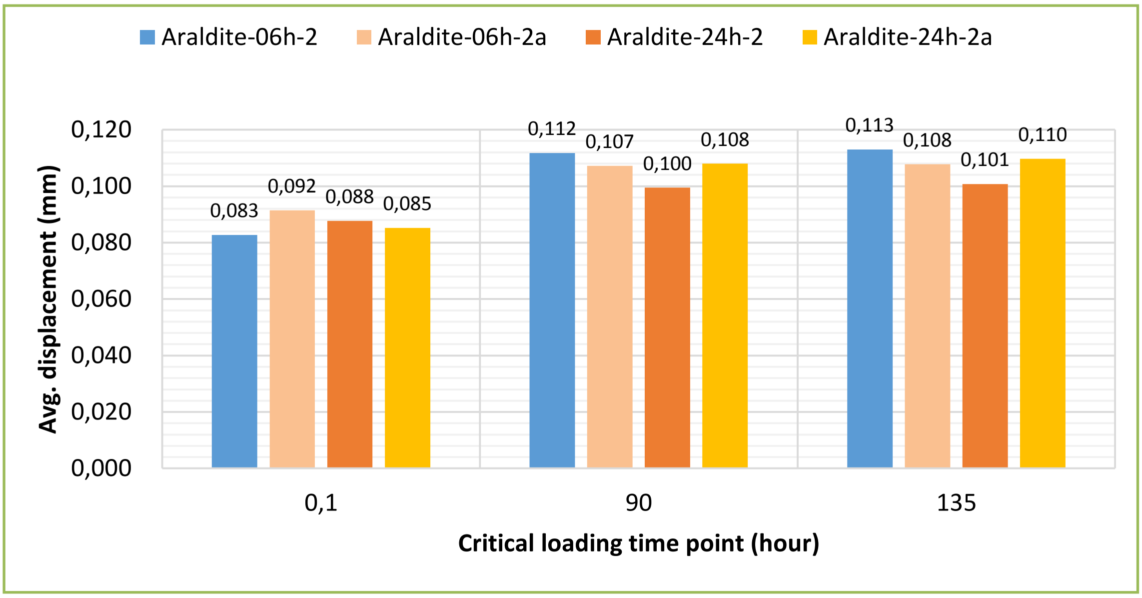


Figure 2.21: Histogram of Avg. displacement at critical time point (Araldite - Constant Load)

Therefore from Figure 2.21, we can find that the difference between two specimens with the same curing time sometimes even more larger than the difference between two specimens with the different curing time.

Based on the results shown in Figure 2.21 and listed in Table 2.11 and 2.12, we can draw a conclusion that for resin Araldite, the influence caused by different curing time, which are 6 hours and 24 hours adopted in our tests, could be ignored at all. The difference of the average displacements between two specimen with different curing time even less than the same kinds of value between two specimens with the same curing time. It is more uniformity for the two specimens under step load.

Another conclusion can be drawn is that resin Araldite has a very slight creep behaviour. When the specimen has been loading for over 90 hours, the connection's slip would be almost keeping invariability. Most of the slip between outer plates and inner plates had been occurred at the first several hours after loading.

(2) Edilon Dex-R2K

We use the same analytic method for resin Edilon Dex-R2K again.

Firstly, based on the displacement-time curves in Figure 2.20, displacements at some selected critical time points are listed in Table 2.13 for specimens under step load. Taking into account the similarity of the results, only the displacements at LVDT 01/02/11/12 are listed and calculated.

The selection principle of critical time points in Table 2.13 are:

- The first point in time when the load reaches the step preset value, that is 80 kN, 112 kN, and 144 kN. So these three time points are determined by the force value actually
- The time of loading reaches to 90 hours, which is also nearly the unload time of these two specimens

Table 2.13: Displacement at critical time points (Edilon Dex-R2K - Step Load)

Name of specimen	Time point (hours)	Force value (kN)	Displacement (mm)					Normalization	Difference (%)
			Lvdt 01	Lvdt 02	Lvdt 11	Lvdt 12	Avg. of 4 Lvdt		
R2K-06h-1	0.1	80	0.101	0.130	0.117	0.119	**0.117**	1	0
	6	112	0.176	0.220	0.215	0.204	**0.204**	1	0
	12	144	0.220	0.271	0.267	0.252	**0.253**	1	0
	90	144	0.246	0.304	0.301	0.280	**0.283**	1	0
R2K-24h-1	0.1	80	0.086	0.093	0.104	0.119	**0.101**	0.861	-13.9
	6	112	0.142	0.147	0.191	0.210	**0.173**	0.847	-15.3
	12	144	0.188	0.194	0.256	0.274	**0.228**	0.903	-9.7
	90	144	0.229	0.239	0.344	0.358	**0.293**	1.034	+3.4

Note: The normalization values and difference are all based on the first specimen.

From the calculation results in Table 2.13, we can find that the maximum difference is -15.3 % at time point of 6 hours and decrease and reverse to +3.4 % at time point of 90 hours. It seems curing time brings a relatively small impact for these two specimens, especially when the loading time reaches to 90 hours.

By comparing the displacement-time curves of these two specimens in Figure 2.20, we can find the great scatter in specimen R2K-24h-1, the difference between two connections of itself is more large than the difference between these two specimens. In this case, it is difficult to compare the influence of curing time.

Another important result is related to the bearing capacities of the connections. On the bottom connection at specimen R2K-24h-1, the average displacement of LVDT 11 and LVDT 12 at 90 hours loading time point is 0.351 mm, which has exceeded the specification limit of 0.3 mm in EC3. The creep behaviour is more large than resin Araldite.

Secondly, based on the displacement-time curves in Figure 2.20, displacements at some selected critical time points are listed in Table 2.14 for specimens under constant load. Taking into account the similarity of the results, only the displacements at LVDT 01/02/11/12 are listed and calculated.

The selection principle of critical time points in Table 2.14 are:

- The first point in time when the load reaches the preset value, that is 80 kN
- The time of loading reaches to 90 hours
- The time of loading reaches to 95 hours, which is the shortest load time of the four specimens in practice

Table 2.14: Displacement at critical time points (Edilon Dex-R2K - Constant Load)

Name of specimen	Time point (hours)	Force value (kN)	Displacement (mm)					Normalization	Difference (%)
			Lvdt 01	Lvdt 02	Lvdt 11	Lvdt 12	Avg. of 4 Lvdt		
R2K-06h-2	0.1	80	0.095	0.116	0.116	0.146	**0.118**	1	0
	90	80	0.154	0.171	0.201	0.243	**0.192**	1	0
	95	80	0.154	0.171	0.201	0.243	**0.192**	1	0
R2K-24h-2	0.1	80	0.150	0.169	0.129	0.154	**0.151**	1.273	+27.3
	90	80	0.316	0.380	0.289	0.291	**0.319**	1.659	+65.9
	95	80	0.318	0.382	0.290	0.292	**0.321**	1.667	+66.7
R2K-06h-2a	0.1	80	0.109	0.106	0.119	0.122	**0.114**	0.964	-3.6
	90	80	0.161	0.155	0.181	0.185	**0.171**	0.887	-11.3
	95	80	0.161	0.155	0.181	0.185	**0.171**	0.887	-11.3
R2K-24h-2a	0.1	80	0.077	0.099	0.075	0.095	**0.087**	0.732	-26.9
	90	80	0.116	0.142	0.106	0.131	**0.124**	0.644	-35.6
	95	80	0.117	0.142	0.106	0.131	**0.124**	0.645	-35.5

Note: The normalization values and difference are all based on the first specimen.

From the calculation results in Table 2.14, we can find that the maximum difference between R2K-06h-2 and R2K-24h-2 is +66.7 % at 95 hours' time point, the maximum difference between R2K-06h-2 and R2K-24h-2a is -35.6 % at 90 hours' time point. These difference values are very large, but the influence by curing time towards to 2 directions. The disperse between two specimen of 24 hours curing time is enormous.

For further compare the differences between these fours specimens, the average displacements of 4 Lvdts at three critical loading time points also could be drawn with a histogram, which is shown in Figure 2.22.

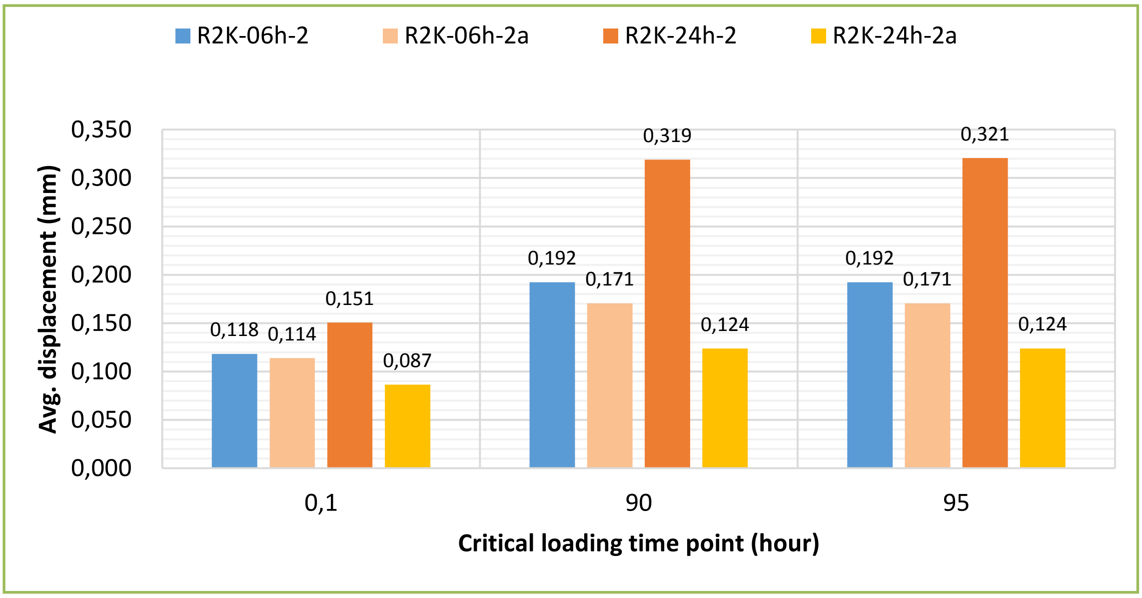


Figure 2.22: Histogram of Avg. displacement at critical time point (Edilon Dex-R2K - Constant Load)

From Figure 2.22 we can find that the average displacement of specimen R2K-24h-2 has exceed 0.3 mm, which lead to a unreliable analysis results for influence of curing time. In spite of this specimen, another 24 hours curing time specimen, the R2K-24-s behaves the minimum creep performance, the displacement at 90 hours' time point is only 0.124 mm, which is very lower than the same kinds of value of the two 6 hours curing time specimens. Furthermore, as we find in Figure 2.17, for resin Edilon Dex-R2K, the discrepancy of the test results are enormous.

2.2.2.3.7 Conclusions

The main conclusion getting from this step can be listed below

- Once again, Araldite, the initial resin recommended in ECCS(1994), has been shown to have good, stable connection bearing capacity through the creep tests in this step.
- Resin Araldite also has a very slight creep behaviour. When the specimen has been loading over 90 hours, the connection's slip would be almost keeping invariability. Most of the slip between outer plate and inner plate had been occurred at the first several hours after loading.
- For resin Araldite, the influence caused by different curing time, which are 6 hours and 24 hours adopted in our tests, could be ignored at all.
- On the other side, Edilon Dex-R2K, the potential alternative resin, has been shown to have unstable connection bearing capacity through the creep tests in this step. Test results of connection's slip value show great difference between different specimens or even between two connections belong to the same specimen.
- For one of the specimen, R2K-24h-2, the slip value even exceed 0.3 mm when loading after 90 hours under constant load. It is worth noting that the load value at constant load is only 80 kN, which is 50 % of the benchmark force value of 0.15 mm slip at CBG of the plates obtained in Step 2.
- In this case, it is difficult to compare the influence of curing time for resin Edilon Dex-R2K. We can simply say that curing time is an unimportant factor for this kinds of resin.
- In the subsequent tests, the influencing parameter for curing time will no longer be considered, but we will keep all the specimen's curing time at least 24 hours after injecting and before loading.

2.2.3 Long term test (Stage 2)

2.2.3.1 Objectives

The present design bearing stress for injection bolts is based on long duration creep tests. Recent research has shown that for short duration loads higher design bearing stresses can be allowed. This is especially important for structures where the main load consists of short duration loads e.g. wind load, such as the new glass roof in the Amsterdam Central Railway Station.

In practice, structure and bridge are bearing with different combination of load cases, such as the dead load, the live load, the wind load, and so on. For simply simulating the load combination in practice, we built up long term test strings and loading them with different load levels along with time to know the creep behaviours of resin.

Furthermore, besides the normal round hole with 2mm clearance, slotted holes with 4mm clearance and 6mm clearance were also used in the specimens of this stage for the purpose of getting a general knowledge of the connection’s creep behaviour influenced by the thickness of resin layer. The long direction in the slotted holes was along the loading direction, which had a large clearance between the bolt shank and the hole wall. So in the tensile direction, the thickness of resin layers were changed by different kinds of hole. But in the perpendicular direction, all the bolt holes kept the same clearance of 2mm. The benefit of it was that the normal stress in all the plate’s net sections would be same on the condition of not changing the specimen’s width.

Two kinds of resin were used again, they are

- Araldite
- Edilon Dex-R2K

The type of holes and clearance are

- Round hole 22 mm, with 2mm clearance
- Slotted hole 24 mm, with 4mm clearance
- Slotted hole 26 mm, with 6mm clearance

The load levels used in loading are

- 0.3 F
- 0.4 F
- 0.5 F
- 0.6 F
- 0.7 F
- 0.8 F
- 0.9 F
- 1.0 F

The ‘F’ value means the load for both of the connection’s slip at the center of the bolt group (CBG) reach to 0.15mm, which were obtained in Stage1 - Step 2. But due to there only one bolt in each connection of the specimens, so the F value is **100 kN** for Araldite and **80 kN** for Edilon Dex-R2K.

From the previous tests we obtained that curing temperature and curing time would not have obviously influence to connection’s mechanical properties, so resin injection and specimen loading had been done in ambient temperature, which was varying slightly between 16 °C to 24 °C during the test period in the Stevin Laboratory.

The curing time was at least 24 hours after injecting and before loading for all of the specimens.

2.2.3.2 Experimental plan

As an initial plan, 4 specimen strings constituted by 16 specimens would be tested, each string including 4 specimens. The main influencing parameters for the initial test are listed in Table 2.15.

Table 2.15: Specimen details of Stage 2 (Initial test)

Bolt type	Bolt size	Hole & Clearance	Resin type	Curing temperature	Curing time (hours)	Name of string	Number of specimens
Non-preloaded	M20 ×80 mm	Round 2mm	Edilon Dex-R2K	Ambient temperature	at least 24	String 1	2
		Slotted 4mm					1
		Slotted 6mm					1
		Round 2mm				String 2	2
		Slotted 4mm					1
		Slotted 6mm					1
		Round 2mm	Araldite			String 3	2
		Slotted 4mm					1
		Slotted 6mm					1
		Round 2mm				String 4	2
		Slotted 4mm					1
		Slotted 6mm					1
Total							**16**

Note: All the specimens listed in the table above have been tested from November, 2016. Thereinto String 1 and String 2 were stopped loading at February, 2017.

During the loading process, to be exact, at January 5th, 2017, when we ascending the tension load value of String 4 from 0.6 F to 0.7 F, the pin connection on the top of the load cell broke suddenly and caused this string collapse immediately. Other strings also suffered various degree of impact by this accident. So all the measurement data would be influenced by this ‘shock load’.

After rebuild String 4 and continuously observed for a period of time, we decided to dismantle String 1 and String 2 due to resin Edilon Dex-R2K’s unstable bearing capacity, and to build up 2 new strings for supplementary test. Because the resin Edilon Dex-R2k was not good enough for an alternative resin by the results we got from this stage and the previous stage’s test, only Araldite would been used. So that is the supplementary test, which has the same experimental conditions as the initial test.

The main influencing parameters of these supplemental testing are listed in Table 2.16.

Table 2.16: Specimen details of Stage 2 (Supplementary)

Bolt type	Bolt size	Hole & Clearance	Resin type	Curing temperature	Curing time (hours)	Name of string	Number of specimens
Non-preloaded	M20 ×80 mm	Round 2mm	Araldite	Ambient temperature	at least 24	String 5	2
		Slotted 4mm					1
		Slotted 6mm					1
		Round 2mm				String 6	2
		Slotted 4mm					1
		Slotted 6mm					1
Total							**8**

Note: All the specimens listed in the table above have been tested from February, 2017.

2.2.3.3 Dimension of specimen

In Stage 2, new plates had been designed and ordered. Due to the limitation of the total length of test string, for one specimen, only one injection bolt designed at each of the two connections, the injection bolt size was M20, varied by the hole type and clearance. At both end of the inner plate, there was a M24 normal bolt for connection.

There are 4 specimens including in one string, from top to bottom they are specimen 1 (26 mm hole), specimen 2 (24 mm hole), specimen 3 (22 mm hole) and specimen 4 (22 mm hole). The dimension of the specimens are shown in Figure 2.23.

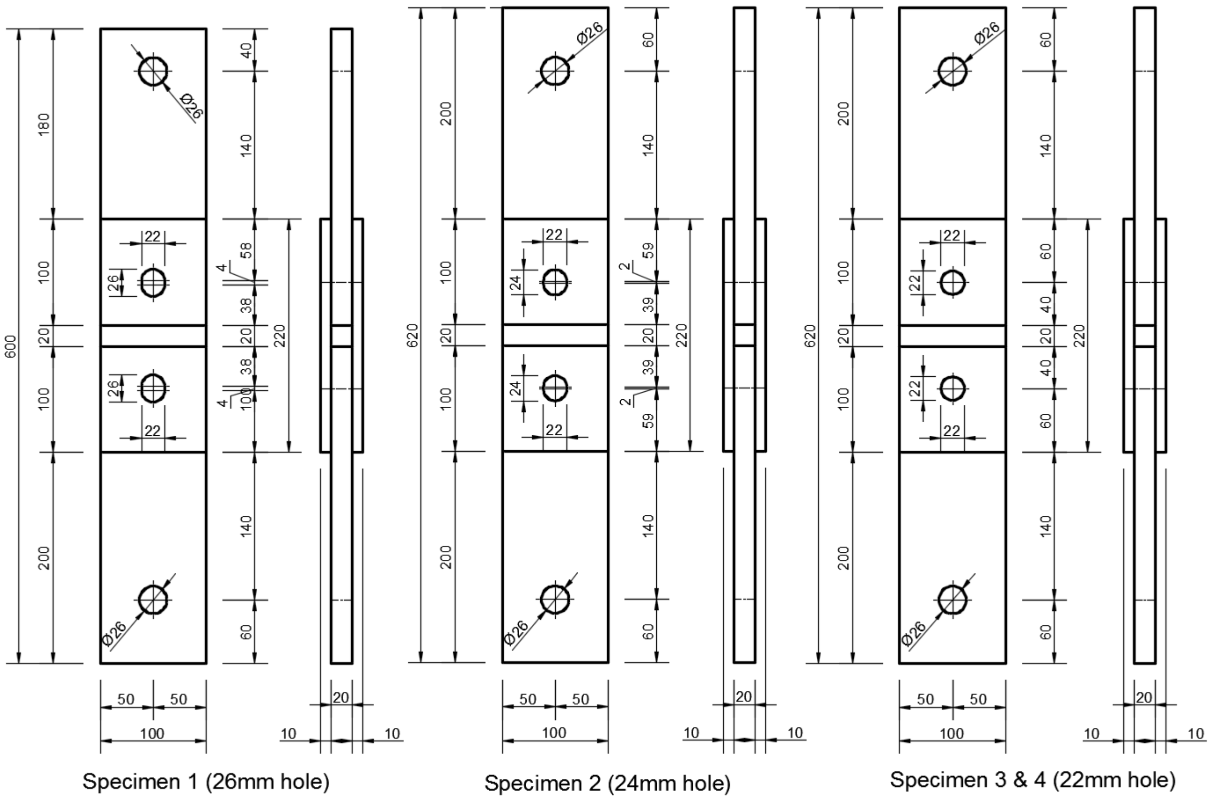


Figure 2.23: Dimension of specimen of stage 2

2.2.3.4 Specimen string establish

For each of the specimen strings, four specimens were connected from top to bottom by the connection plates. On the top of the string there was a load cell connected with a pin connection, then on the top of the load cell there was another pin connection. The strings were established vertically inside a steel frame. On the top of the frame’s top beam, the string were connected with a set of springs for loading by manual tightening three bolts inside the springs.

All of the specimens were injected before building the string, and waiting for at least 24 hours for resin curing. Then the LVDTs were pasted at the correct location of the specimens, 4 LVDTs in each of specimen. When all these preparing works had been done, then we could establish the strings one by one.

The string connection diagram is shown in Figure 2.24. The steel frame is shown in Figure 2.25, inside the frame, four strings had already been established. One of the load cell before building is shown in Figure 2.26. The 4 set of springs used for loading on the top of the steel frame are shown in Figure 2.26.

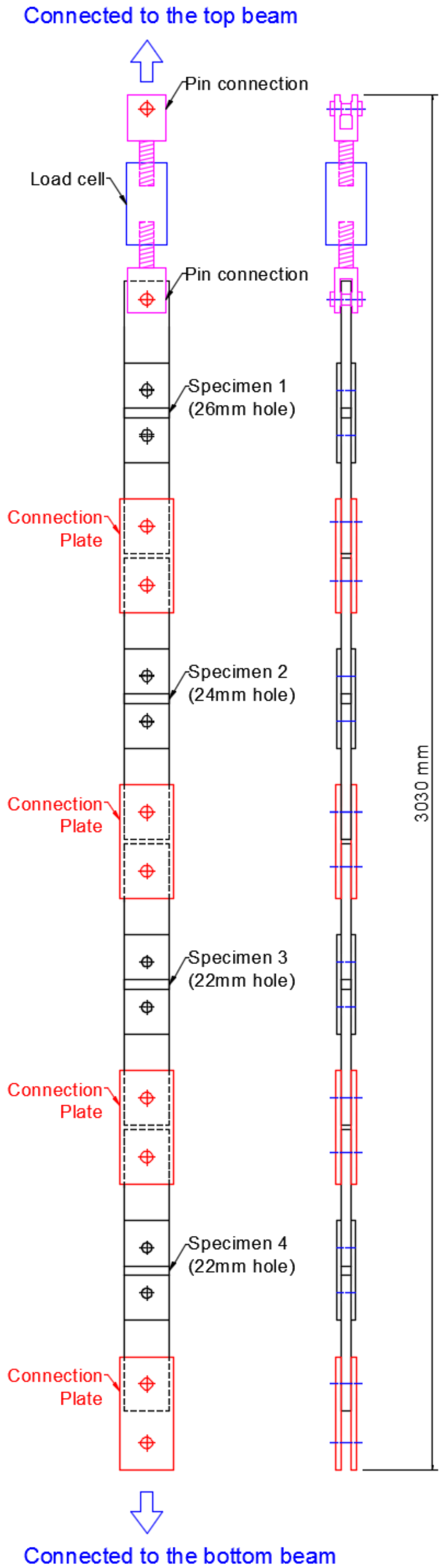


Figure 2.24: Connection diagram of the test string

Figure 2.25: Steel frame with 4 strings established inside

Figure 2.26: Load cell **Figure 2.27: Four spring sets for loading**

2.2.3.5 Measurement setup

In each of the specimens, we used 4 LVDTs to measure the displacements between the outer plates and the inner plates. Therefore in total we used 64 LVDTs for 16 specimens in the test. The LVDT's measurement range is 10 mm and the accuracy is 0.001 mm. In the initial test, the correspondence relationship between the specimens and the LVDTs are listed in Table 2.17.

Table 2.17: Serial number of specimens and LVDTs (Initial test)

Resin type	Name of String	Name of Specimens	Type and clearance of Holes			Serial number and location of LVDTs			
			Type	Clearance	Maximum diameter	Top		Bottom	
						Bolt	Nut	Bolt	Nut
Edilon Dex-R2K	String 1	String 1 - 01	Slotted	6mm	26mm	01	02	03	04
		String 1 - 02		4mm	24mm	05	06	07	08
		String 1 - 03	Round	2mm	22mm	09	10	11	12
		String 1 - 04				13	14	15	16
	String 2	String 2 - 01	Slotted	6mm	26mm	17	18	19	20
		String 2 - 02		4mm	24mm	21	22	23	24
		String 2 - 03	Round	2mm	22mm	25	26	27	28
		String 2 - 04				29	30	31	32
Araldite	String 3	String 3 - 01	Slotted	6mm	26mm	33	34	35	36
		String 3 - 02		4mm	24mm	37	38	39	40
		String 3 - 03	Round	2mm	22mm	41	42	43	44
		String 3 - 04				45	46	47	48
	String 4	String 4 - 01	Slotted	6mm	26mm	49	50	51	52
		String 4 - 02		4mm	24mm	53	54	55	56
		String 4 - 03	Round	2mm	22mm	57	58	59	60
		String 4 - 04				61	62	63	64

The LVDTs had been pasted on the surface of the inner plate just close to the edge of the outer plate with a kind of glue. It must be careful to ensure the LVDTs were located in the center of the plate width and keeping perpendicular with the plate edge. One specimen is shown in Figure 2.28, which had been just pasted with four LVDTs and marked with the serial numbers.

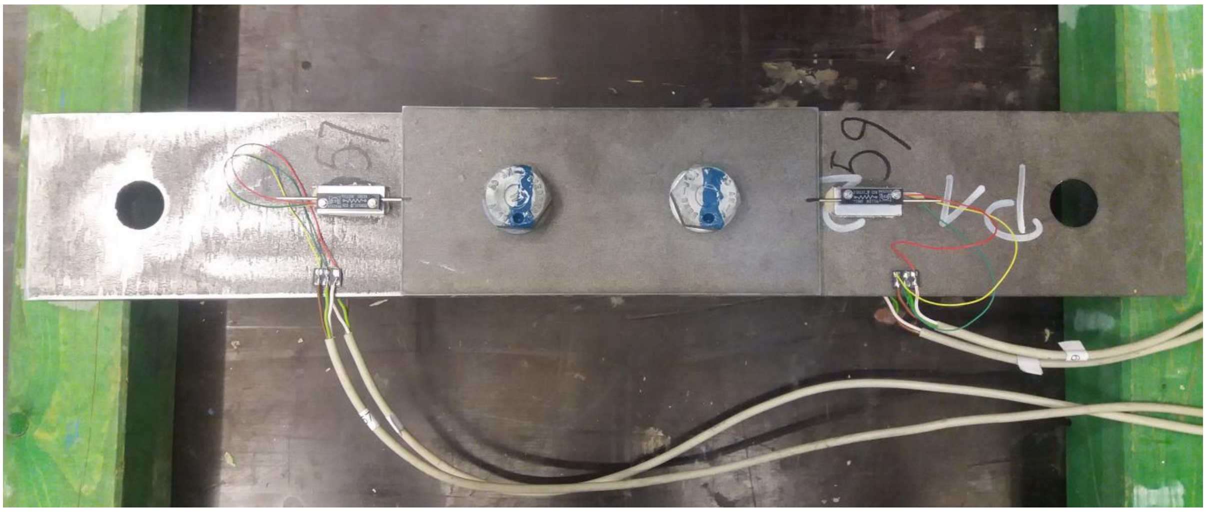


Figure 2.28: One specimen pasted with 4 LVDTs

As we described before, at February 2nd, 2017, we unloaded and dismantled two strings using resin Edilon Dex-R2K, that is String 1 and String 2. After that we injected 8 new specimens with resin Araldite, 6 of them we used new plates and 2 of them we used old plates, which is from String 1 - 04 and String 2 - 04, but cleaning the resin layer and glue thorough before reuse. The other 6 specimens in R2K strings, whose names are String 1 - 01, String 1 - 02, String 1 - 03, String 2 - 01, String 2 - 02, String 2 - 03, will be retest by short term static load later.

Therefore, for the two new strings with resin Araldite, we named them String 5 and String 6 to show the difference and the same kinds of measurement setups will be used again. But since they occupied the original location of String 1 and String 2, so LVDT 01 to LVDT 32 were reused again in the supplementary tests.

The correspondence relationship between the specimens and the LVDTs are listed in Table 2.18.

Table 2.18: Serial number of specimens and LVDTs (Supplementary)

Resin type	Name of String	Name of Specimens	Type and clearance of Holes			Serial number and location of LVDTs			
			Type	Clearance	Maximum diameter	Top		Bottom	
						Bolt	Nut	Bolt	Nut
Araldite	String 5	String 5 - 01	Slotted	6mm	26mm	01	02	03	04
		String 5 - 02		4mm	24mm	05	06	07	08
		String 5 - 03	Round	2mm	22mm	09	10	11	12
		String 5 - 04				13	14	15	16
	String 6	String 6 - 01	Slotted	6mm	26mm	17	18	19	20
		String 6 - 02		4mm	24mm	21	22	23	24
		String 6 - 03	Round	2mm	22mm	25	26	27	28
		String 6 - 04				29	30	31	32

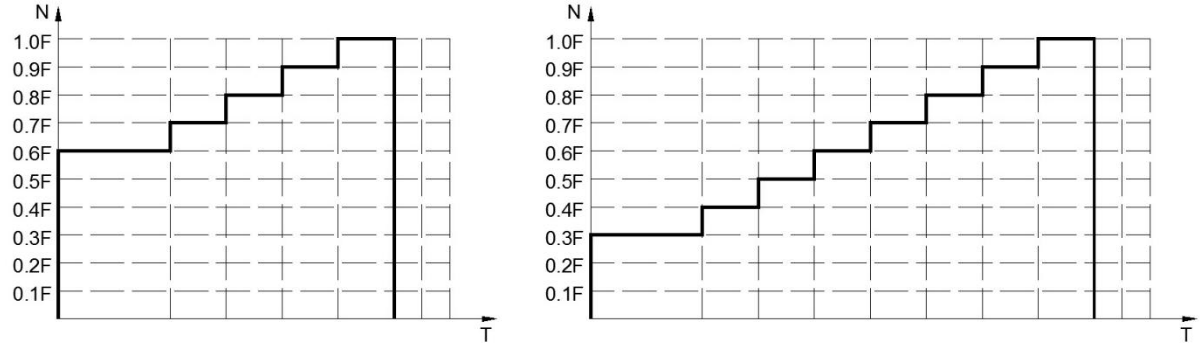
As shown in Figure 2.26 and Figure 2.27, we used 4 sets of spring system to load the test strings by manual. The load cell has a tensile capacity of 100 kN accordance with 2000 μStrain, but by pretesting it could be bearing a tension force about 150 kN. The loading method was tighten the bolts inside the springs manually. In order to uniform the deformation of the spring set, three load bolts must be tightened in sequence with the same rotate angle.

2.2.3.6 Test procedure

2.2.3.6.1 Initial test

According to the original experimental plan, the loading procedure could be described in Figure 2.29. String 1 and String 3 have the same loading step sequence, the first loading step is 0.6 F, that is 48 kN for String 1 and 60 kN for String 3. Meanwhile String 2 and String 4 have the same loading step sequence, the first loading step is 0.3 F, that is 24 kN for String 2 and 30 kN for String 4. After the first step of loading, the subsequent loading steps will be increased by 0.1 F each time until reach to 1.0 F. The load values of each step are listed in Table 2.19.

In Figure 2.29, the horizontal axis is time. The time interval of each loading step can not be predetermined and needs to be determined according to test results about the creep behaviour of the specimens. In general, however, the time interval for each loading step may be one to several weeks. Therefore, the interval in Figure 2.29 with respect to the abscissa is only indicative.



(a) String 1 & String 3 **(b) String 2 & String 4**

Figure 2.29: Loading sequence of Stage 2

Table 2.19: Value of load steps (Unit: kN)

Resin	Name of String	0.3 F	0.4 F	0.5 F	0.6 F	0.7 F	0.8 F	0.9 F	1.0 F
Edilon Dex-R2K	String 1	-	-	-	48	56	64	72	80
	String 2	24	32	40	48	56	64	72	80
Araldite	String 3	-	-	-	60	70	80	90	100
	String 4	30	40	50	60	70	80	90	100

We had established all of the four strings at November 23th and 24th, and started the first step of loading at November 28th, then ccontinuous loading according to Figure 2.29.

As we described before, at January 5th, 2017, when we ascending the load value of String 4 from 60 kN to 70 kN, the pin connection on the top of the load cell had broken suddenly and caused this string collapse. Although we restored String 4 immediately but other strings also suffered various degree of impact by this accident.

After the accident, we kept loading at 0.7 F not changed for all of the four strings. Until February 2nd, we unloaded and disassembled String 1 and String 2, meanwhile kept loading at 0.7 F for String 3 and String 4.

All of specific loading information described above are listed in Table 2.20. The numbers in the bracket below the date in Table 2.20 are the loading time point counted by day form the beginning of loading.

Table 2.20: Actual time schedule of loading sequence (Initial test)

Resin	Name of String	2016				2017			
		11.28 (0)	12.15 (17)	12.22 (24)	12.29 (31)	01.05 (38)	02.02 (66)	02.10 (74)	…
Edilon Dex-R2K	String 1	48	56	56	56	56	0	-	-
	String 2	24	32	40	48	56	0	-	-
Araldite	String 3	60	70	70	70	70	70	70	…
	String 4	30	40	50	60	70*	70	70	…

Note: * String 4 collapsed due to the broken of pin connection and be restored immediately.

2.2.3.7 Test results and analyses

2.2.3.7.1 Initial test

Test of String 1 and String 2 had already been finished, but test of String 3 and String 4 have been continuing. The test results shown below are ended on February 10th, 2017.

The load time history of every string, the displacement-time curves and the displacement-log time curves of every specimens are shown form Figure 2.30 to Figure 2.41.

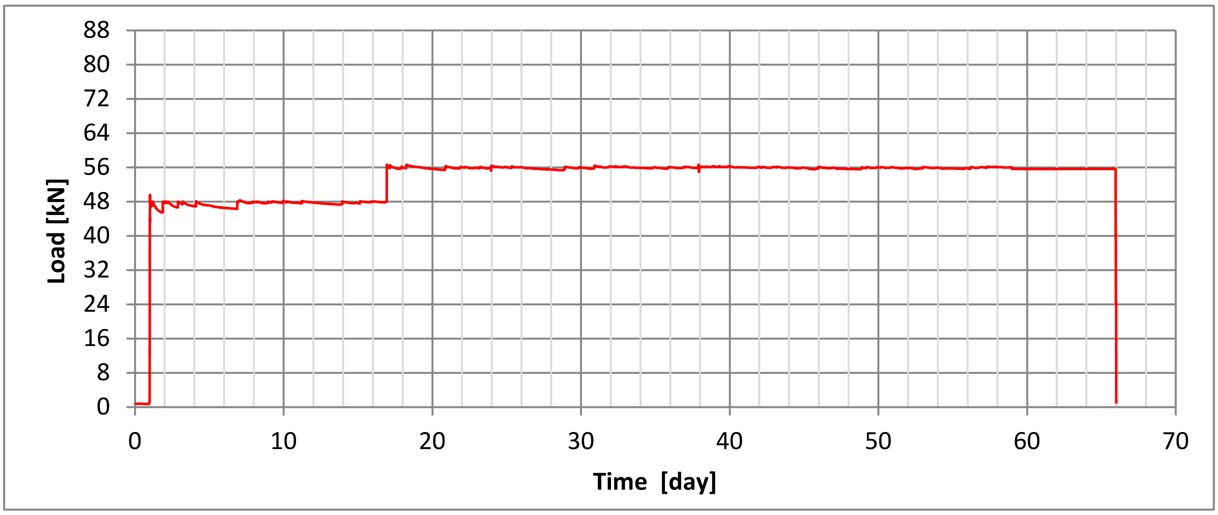
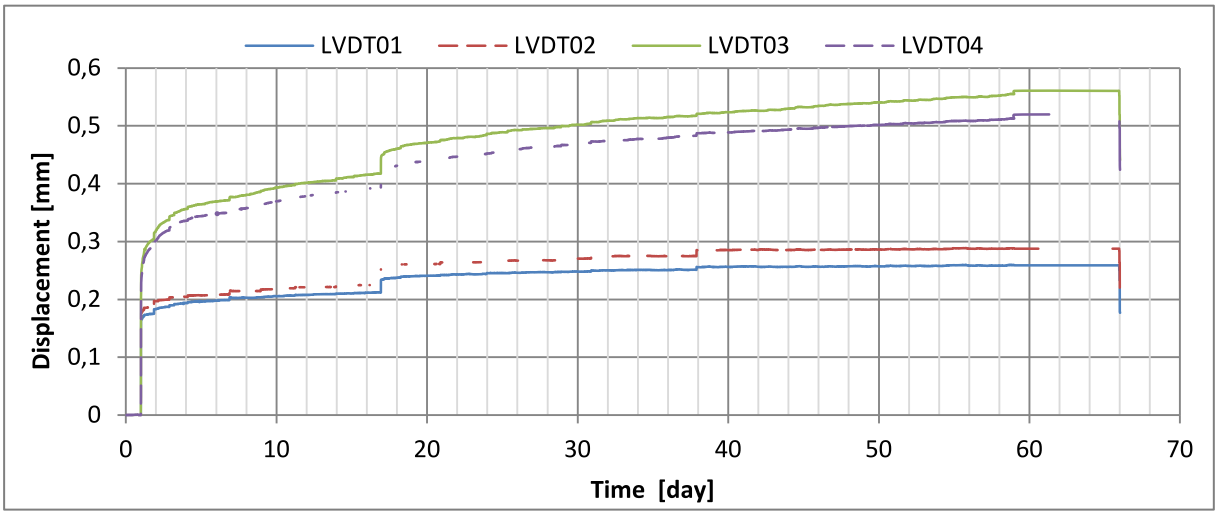
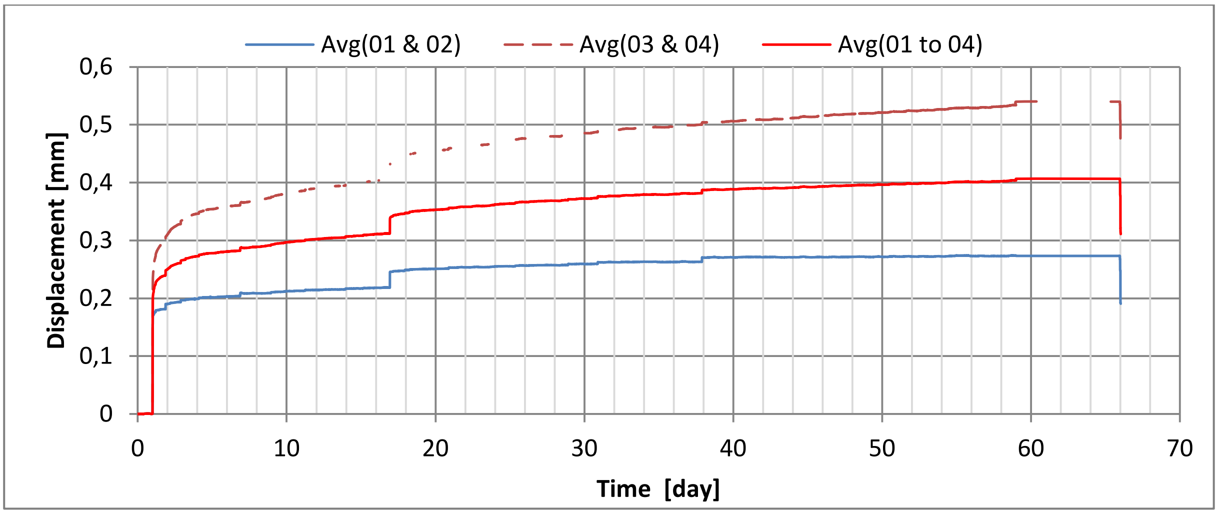
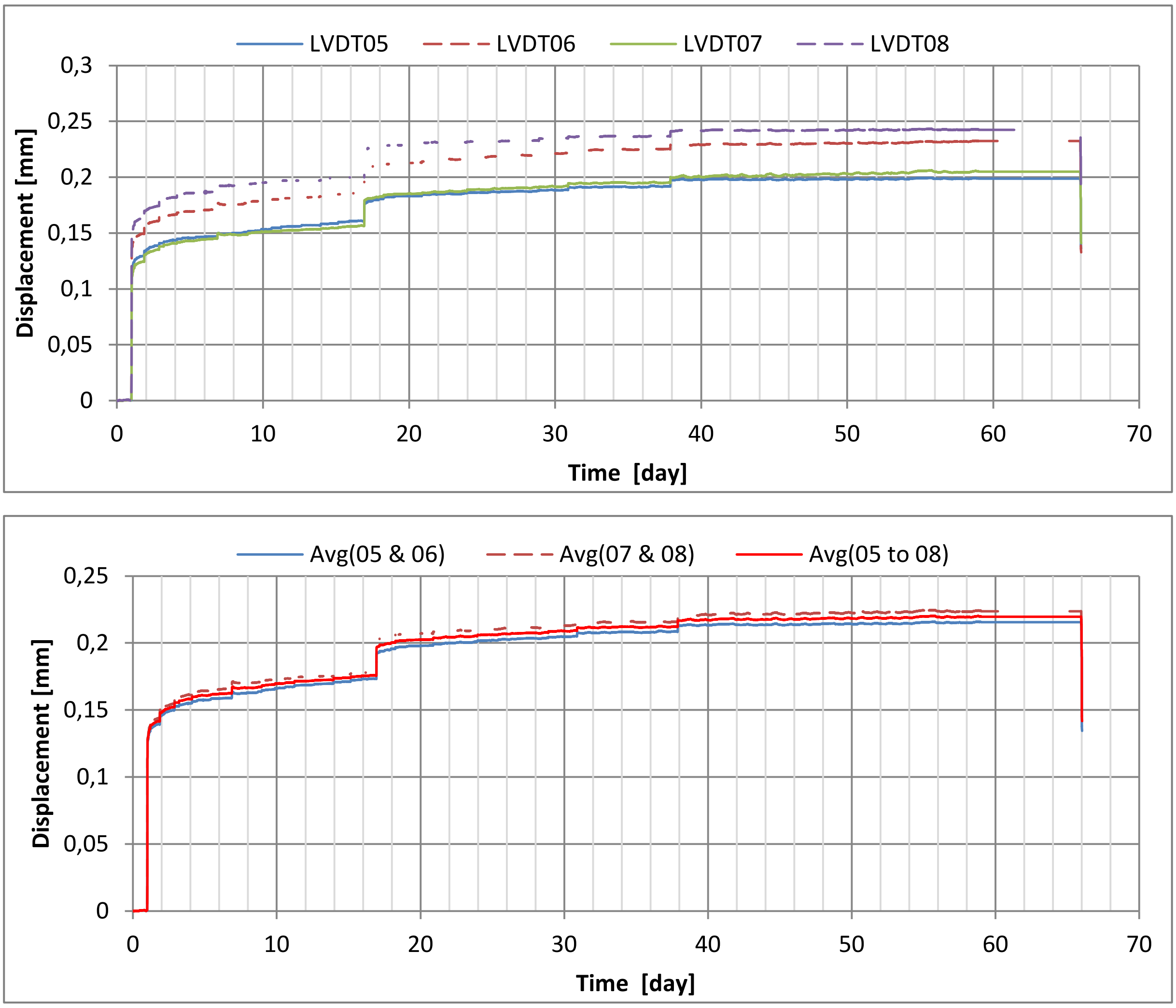


Figure 2.30: Load time history of String 1

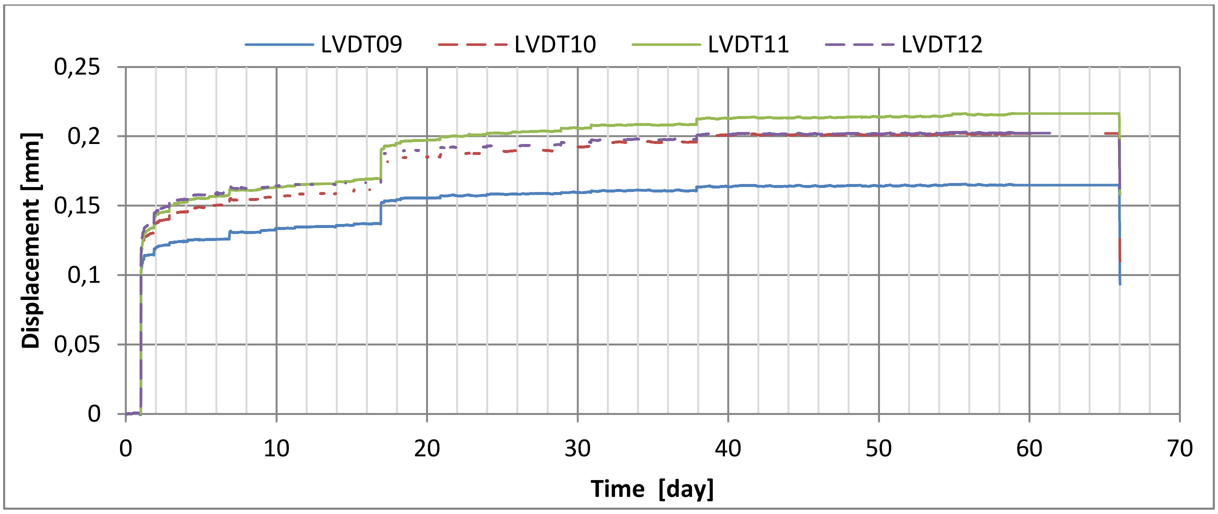


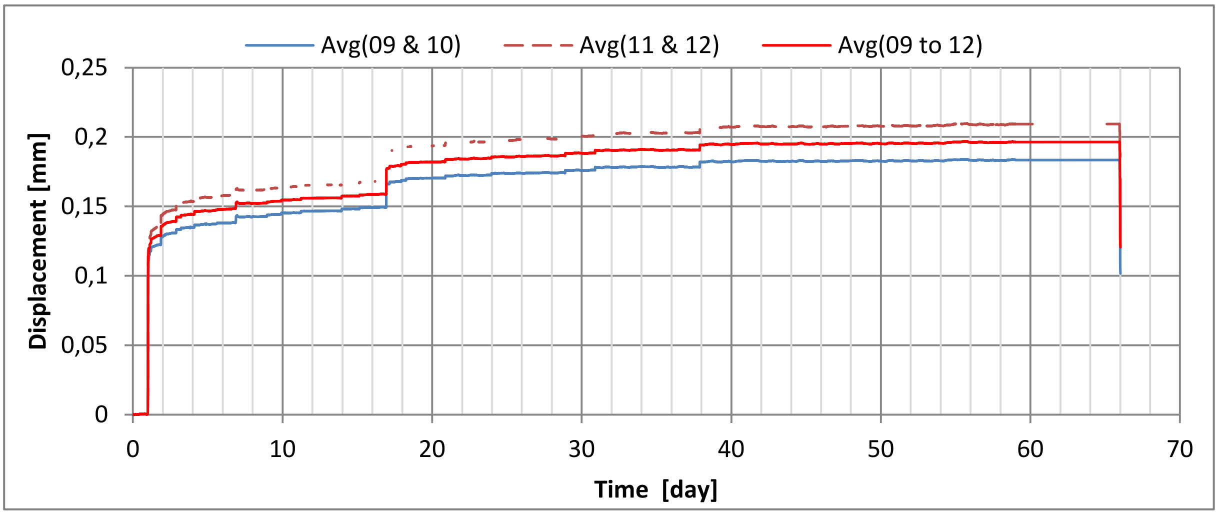


(a) String 1 - 01

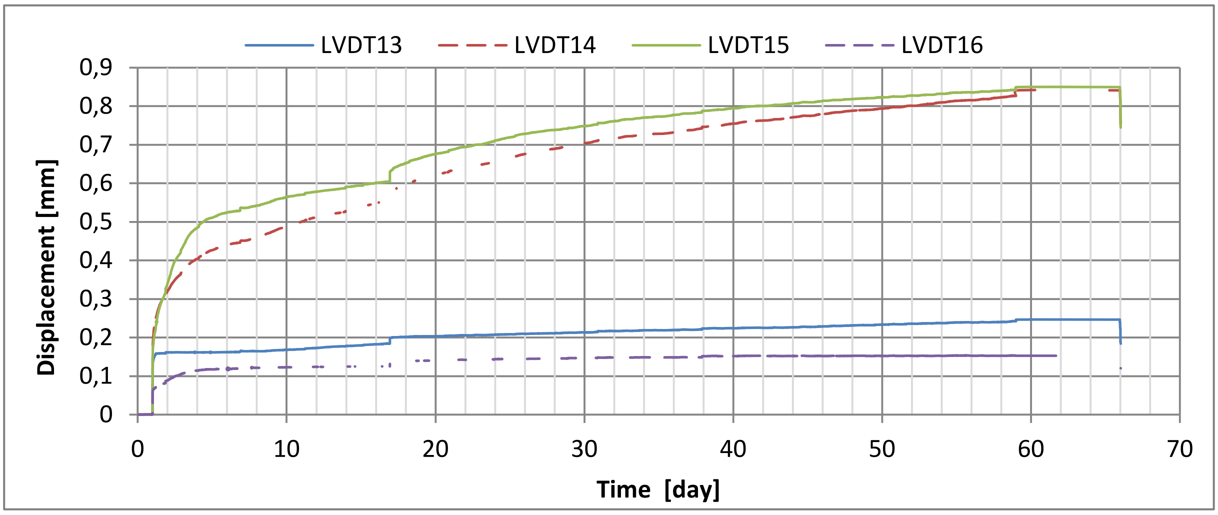


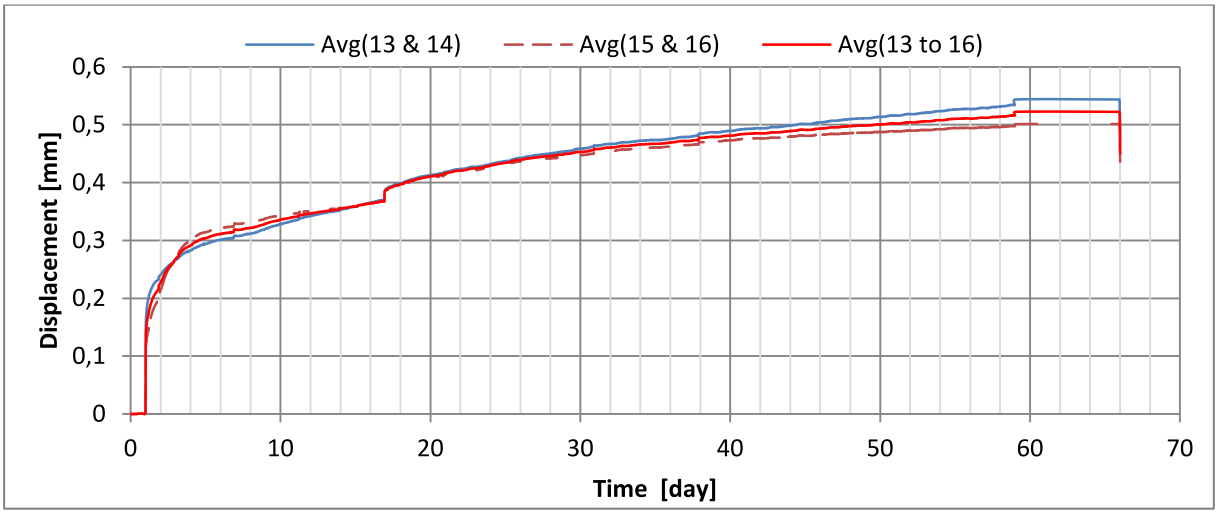
(b) String 1 - 02


LVDT09
LVDT10
LVDT11
LVDT12
Displacement [mm]
Time [day]
0,25
0,2
0,15
0,1
0,05
0
0
10
20
30
40
50
60
70


Avg(09 & 10)
Avg(11 & 12)
Avg(09 to 12)
Displacement [mm]
Time [day]
0,25
0,2
0,15
0,1
0,05
0
0
10
20
30
40
50
60
70

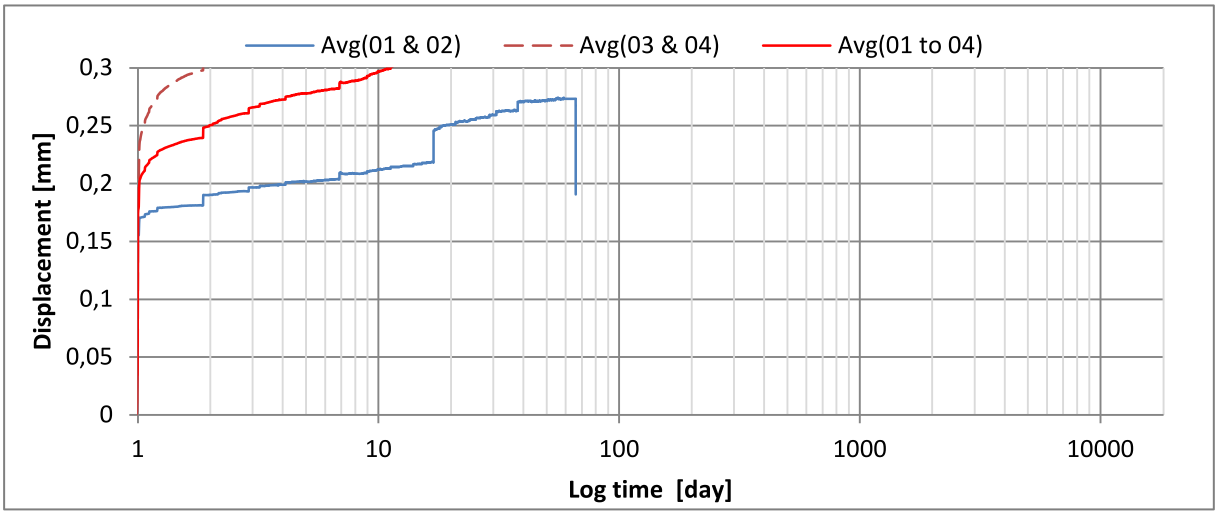
(c) String 1 - 03


LVDT13
LVDT14
LVDT15
LVDT16
Displacement [mm]
Time [day]
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0
10
20
30
40
50
60
70

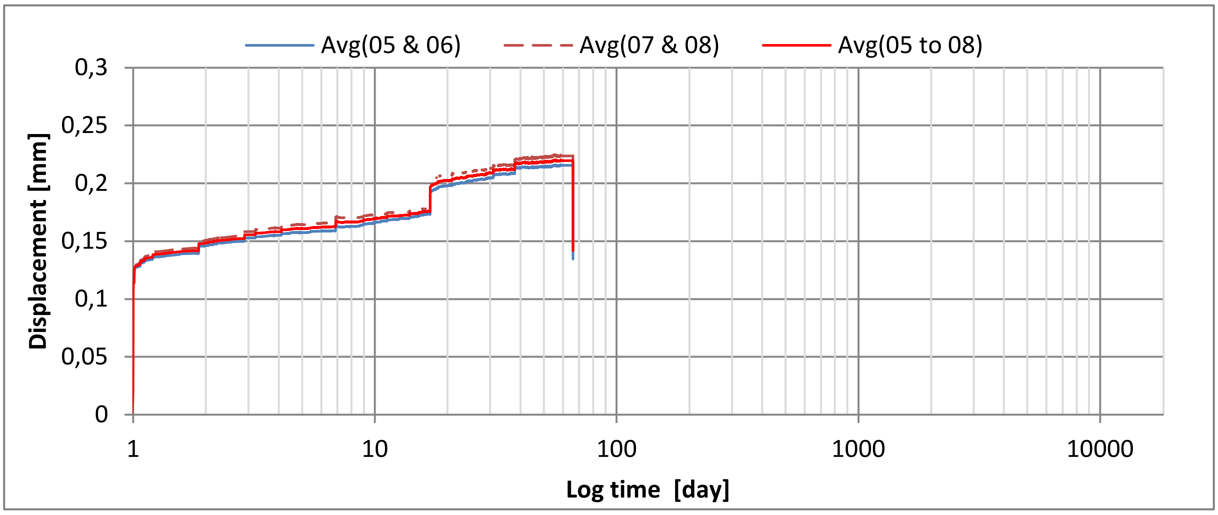


(d) String 1 - 04

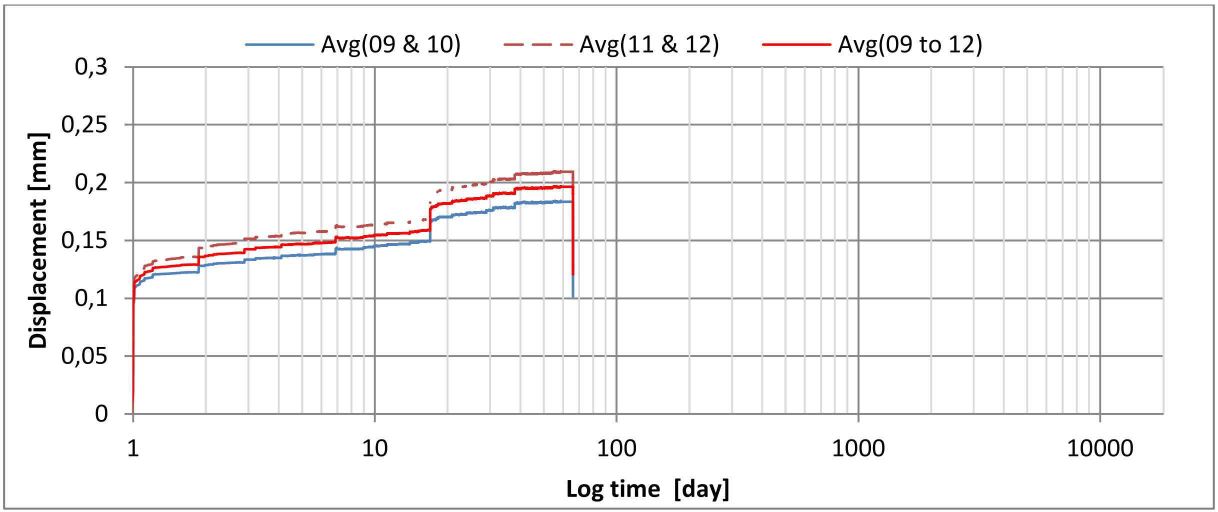
Figure 2.31: Displacement vs time curves of String 1



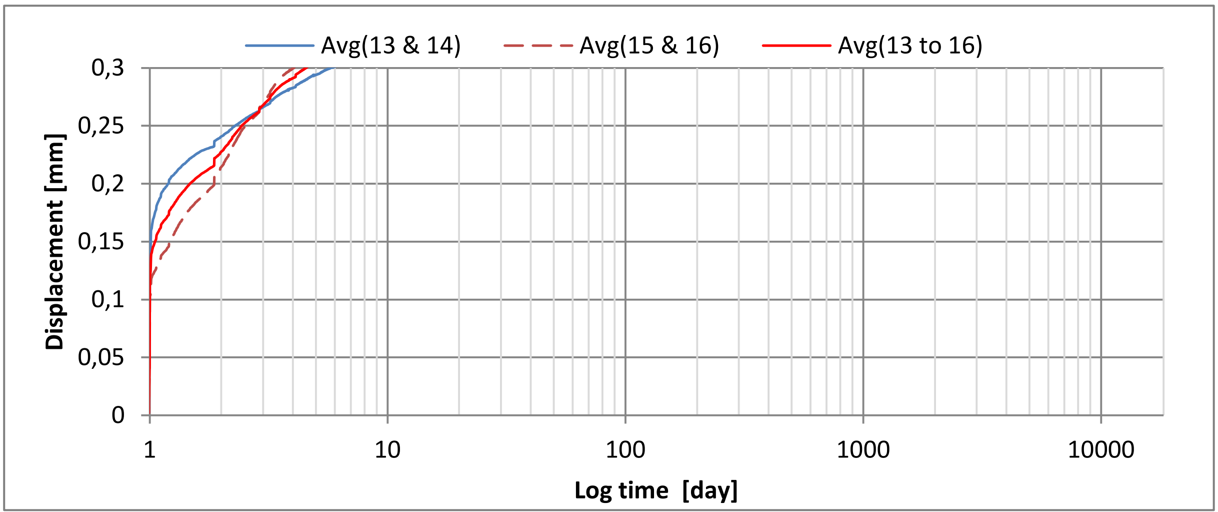
(a) String 1 - 01



(b) String 1 - 02



(c) String 1 - 03



(d) String 1 - 04

Figure 2.32: Displacement vs log time curves of String 1

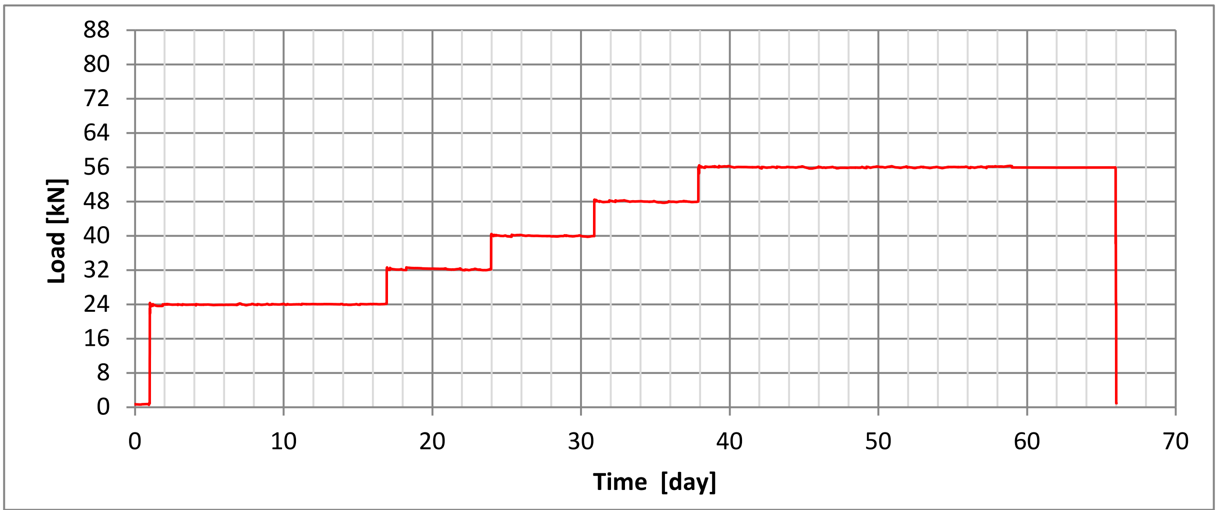
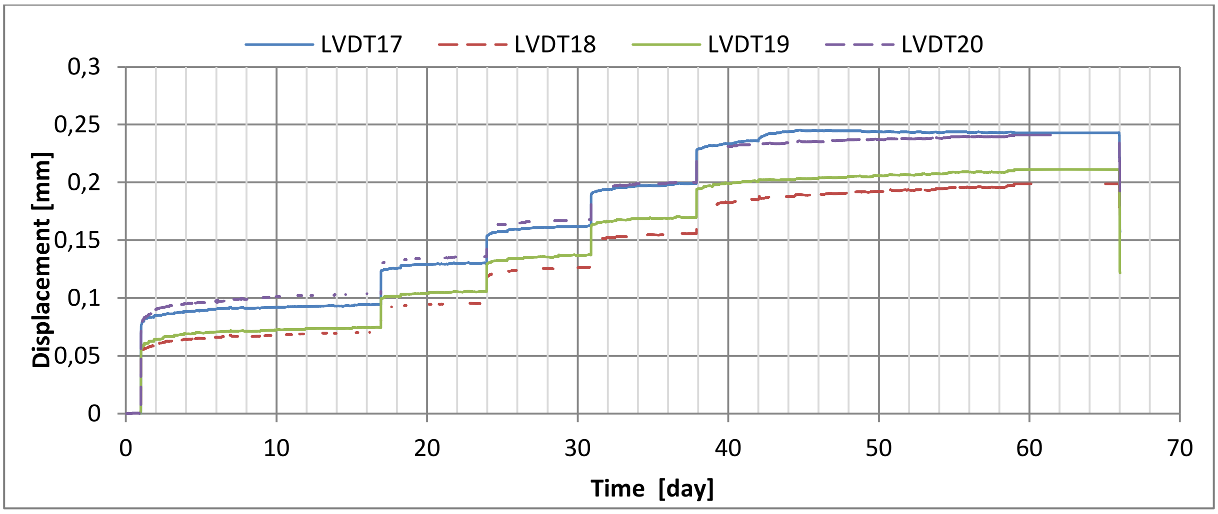
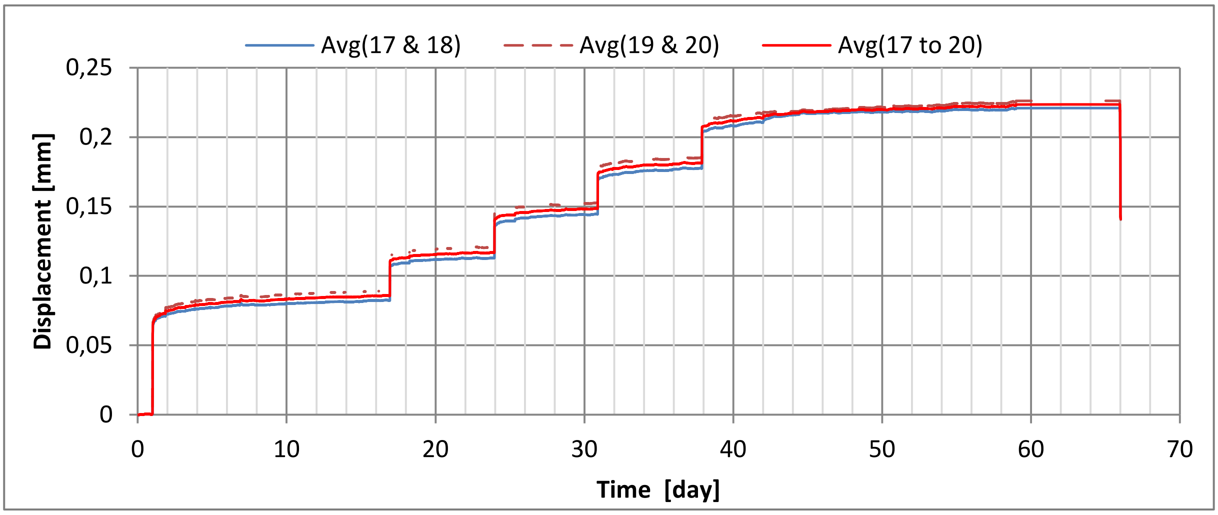
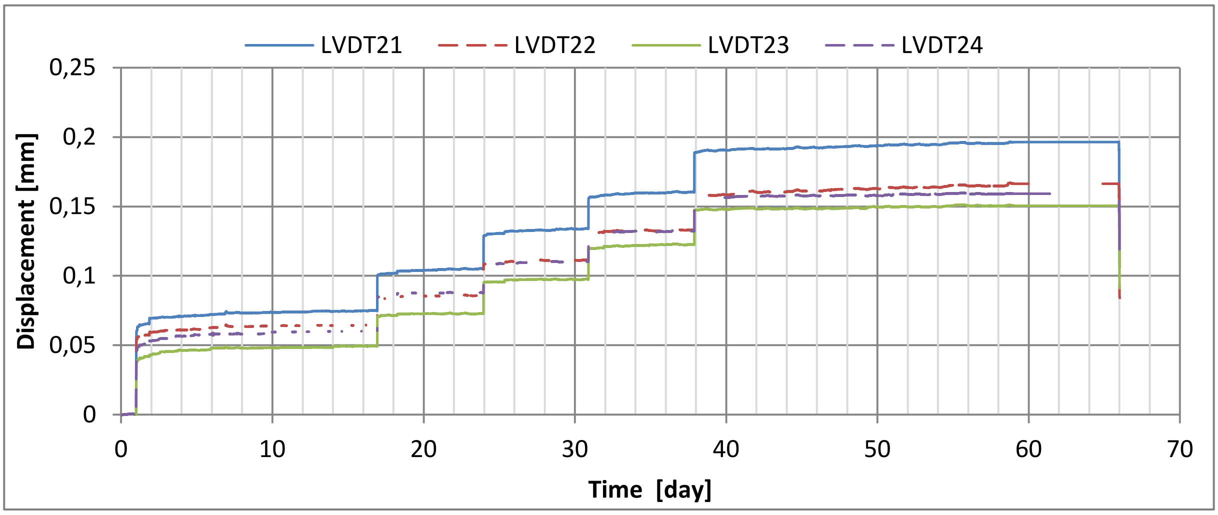


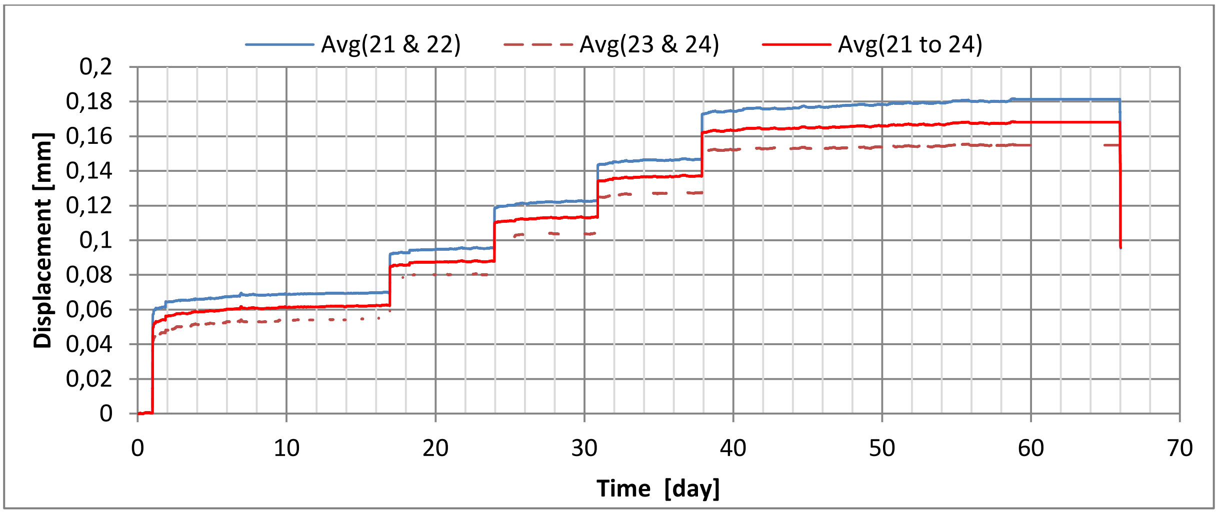
Figure 2.33: Load time history of String 2


LVDT17
LVDT18
LVDT19
LVDT20
Displacement [mm]
Time [day]

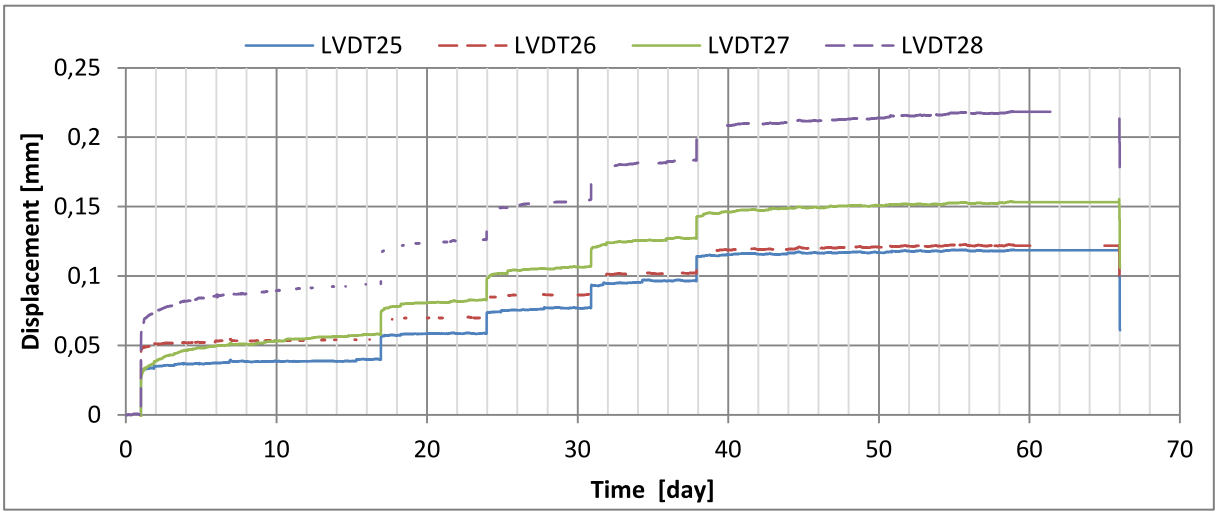

Avg(17 & 18)
Avg(19 & 20)
Avg(17 to 20)
Displacement [mm]
Time [day]

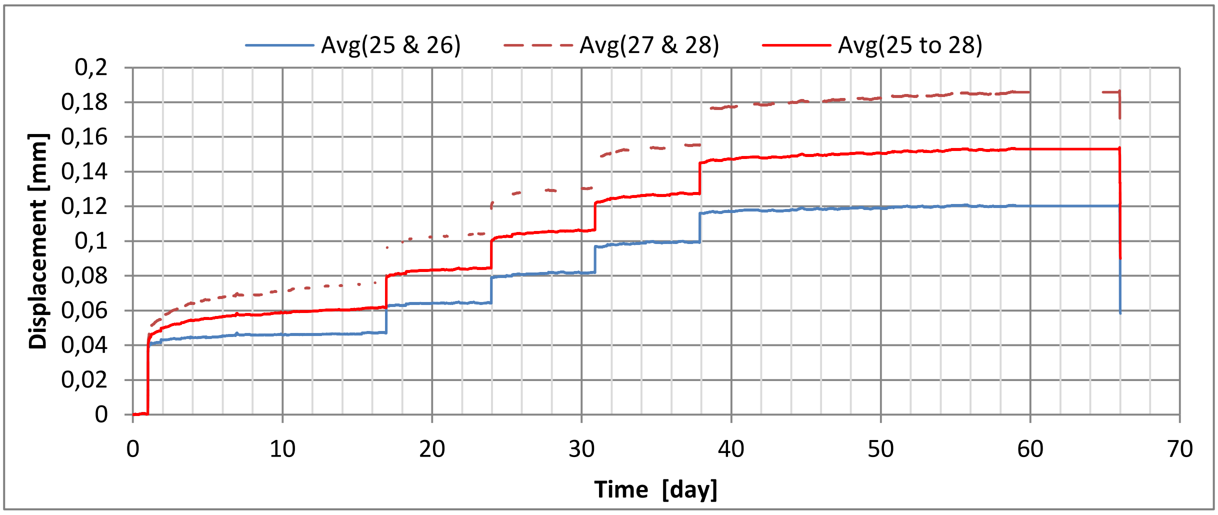
(a) String 2 - 01


LVDT21
LVDT22
LVDT23
LVDT24
Displacement [mm]
Time [day]

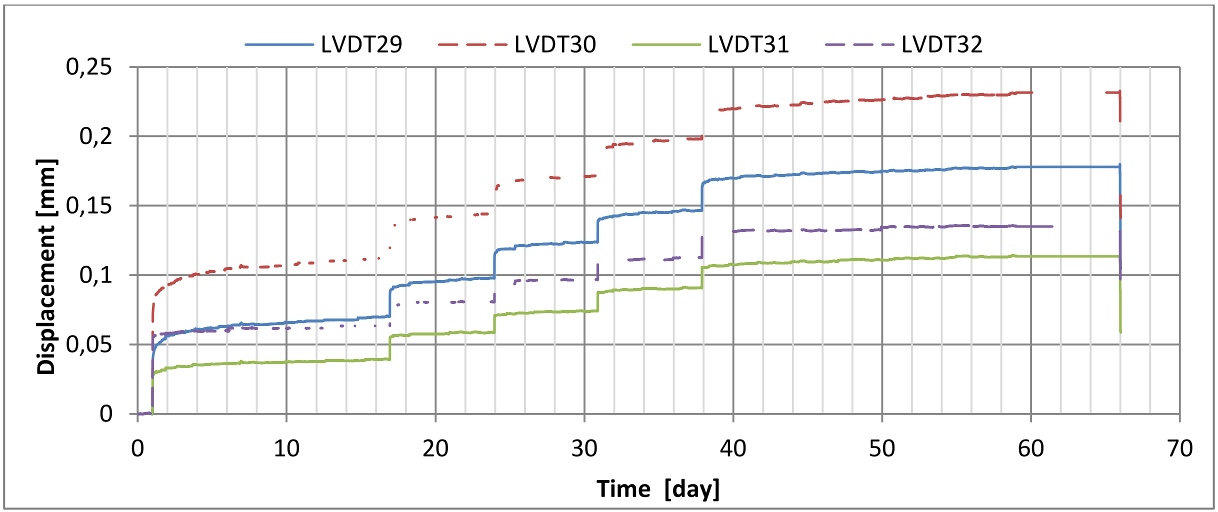


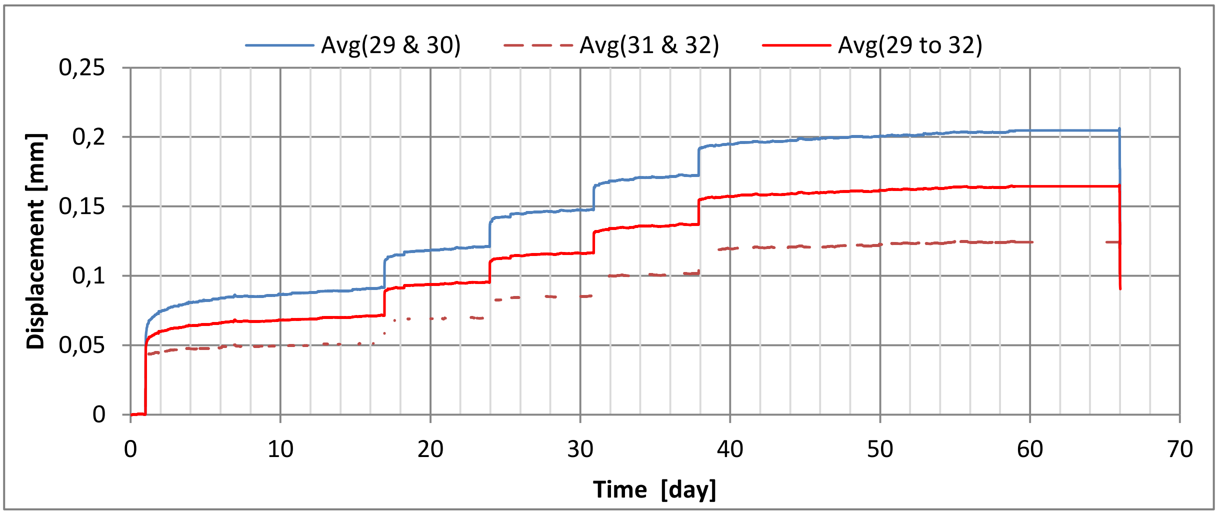
(b) String 2 - 02





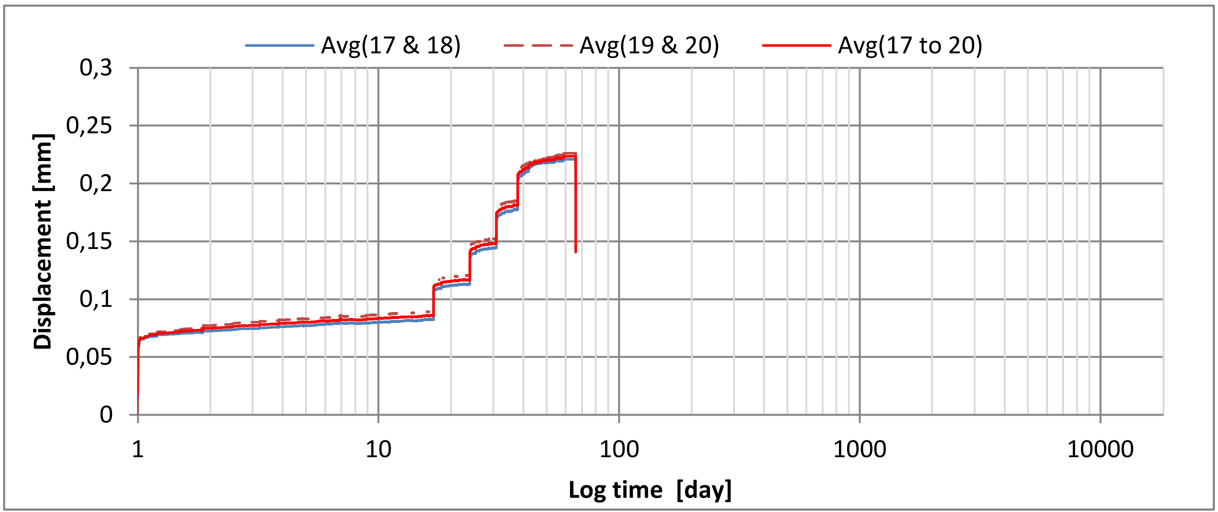
(c) String 2 - 03



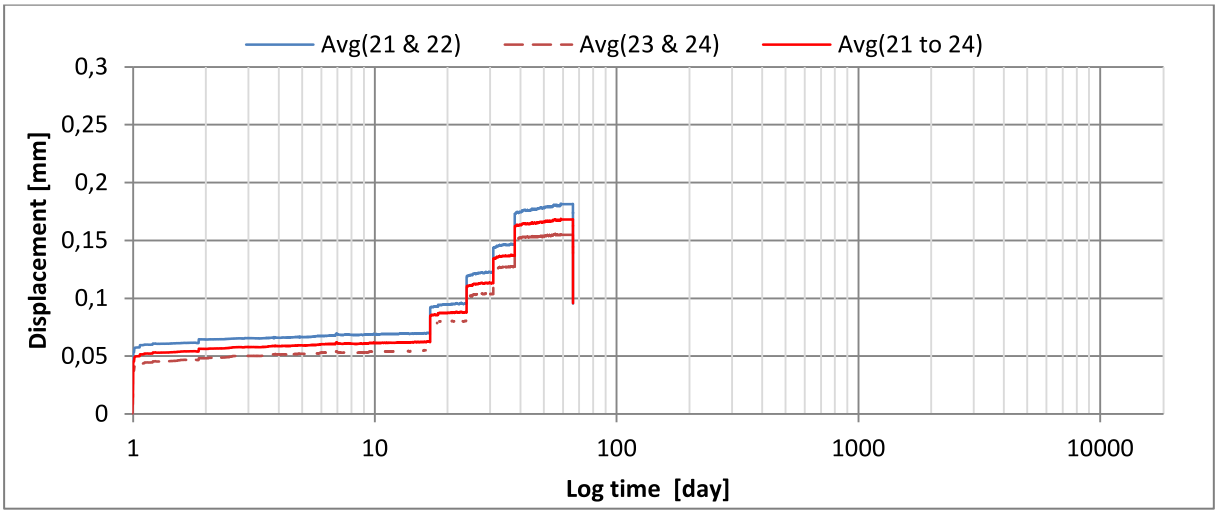


(d) String 2 - 04

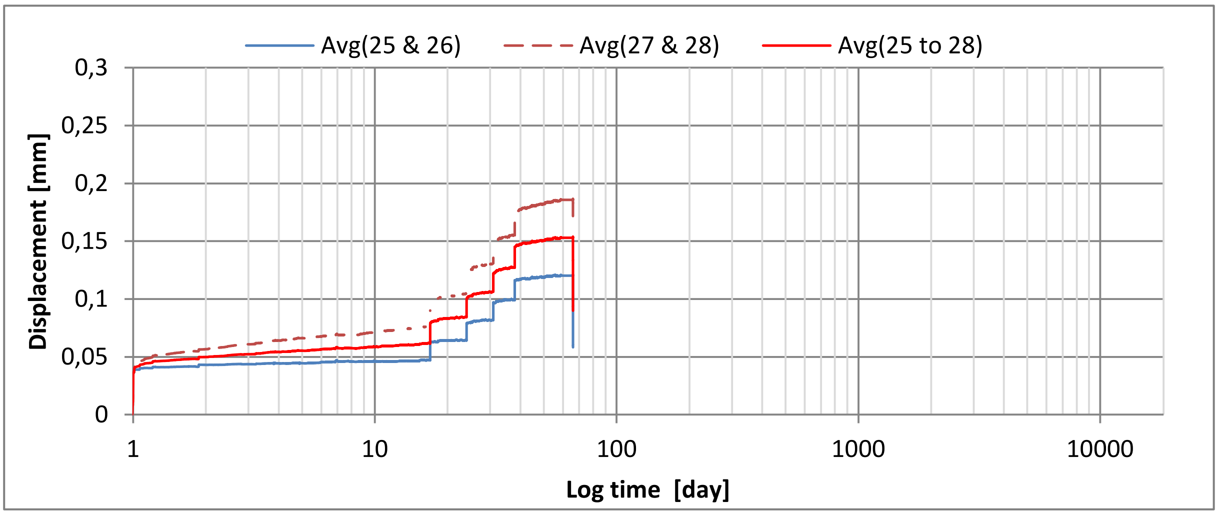
Figure 2.34: Displacement vs time curves of String 2



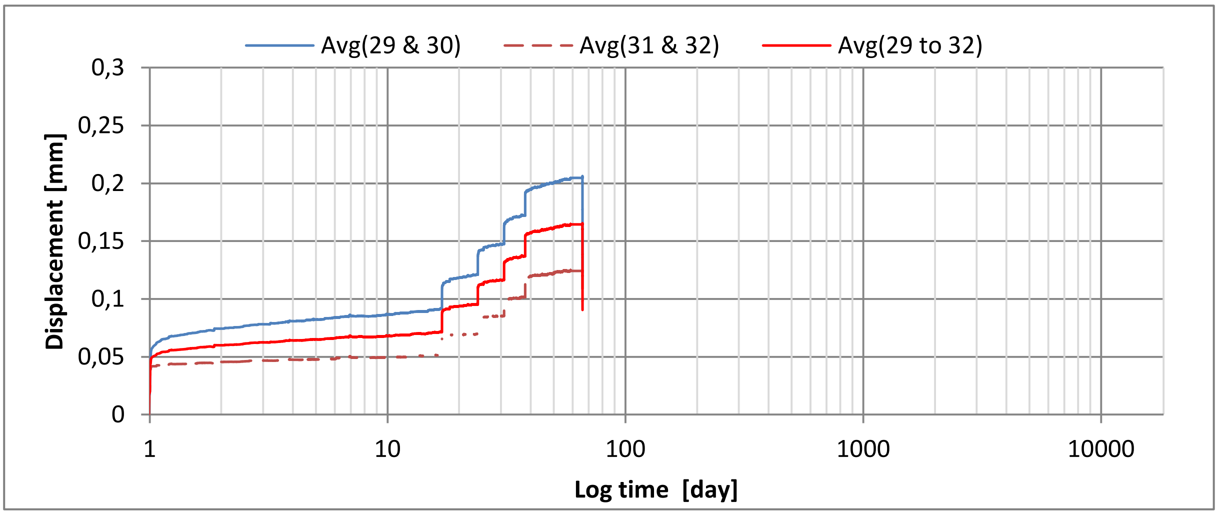
(a) String 2 - 01



(b) String 2 - 02



(c) String 2 - 03



(d) String 2 - 04

Figure 2.35: Displacement vs log time curves of String 2

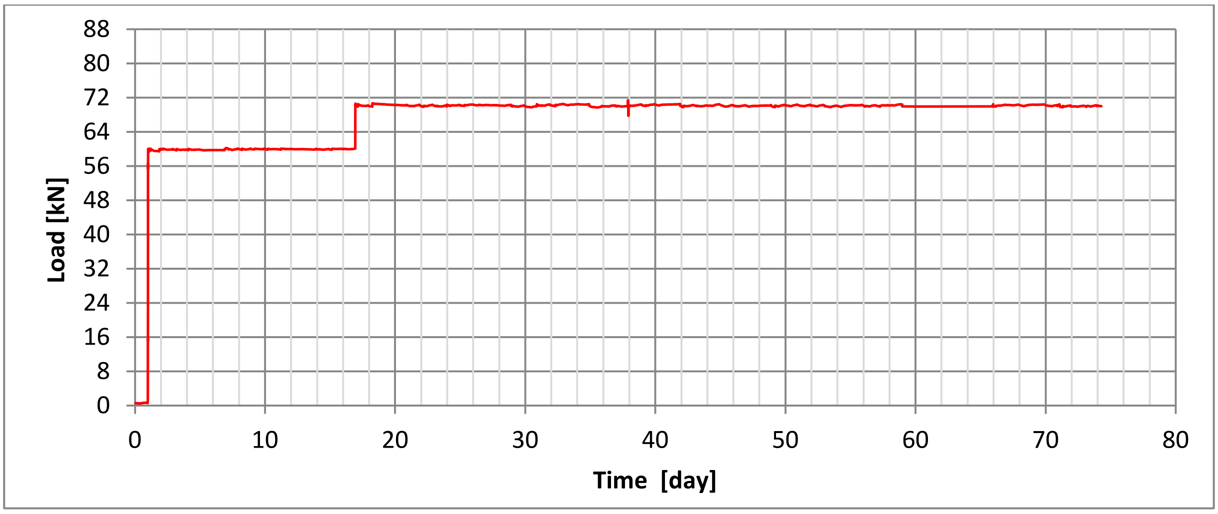
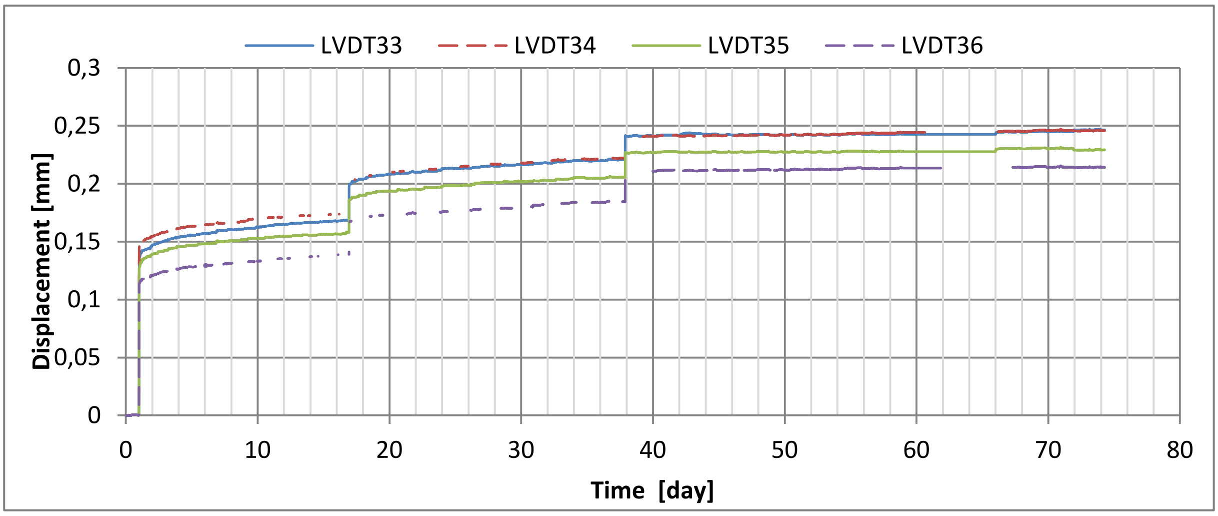
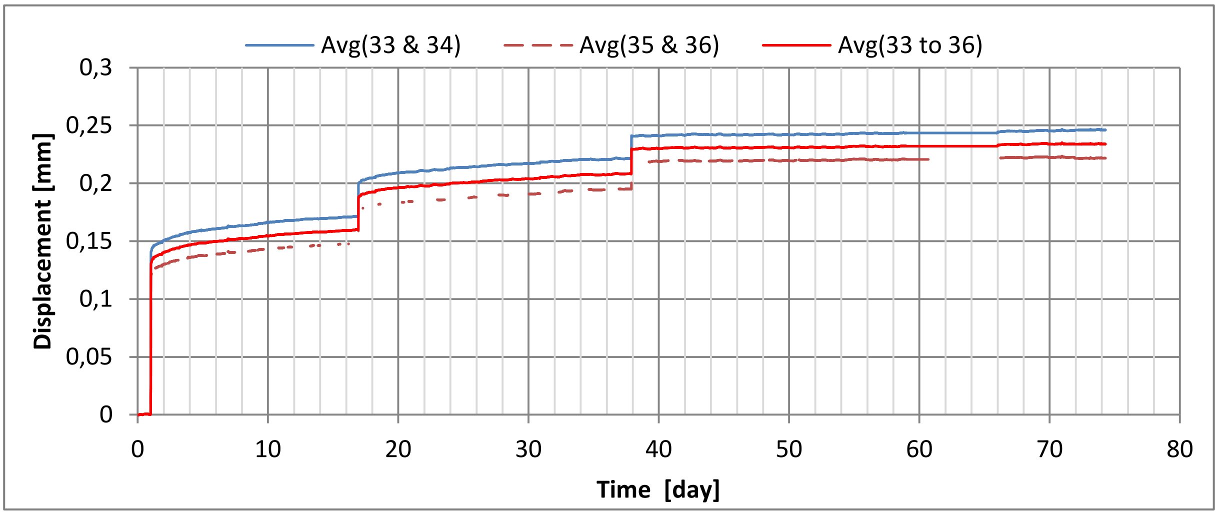
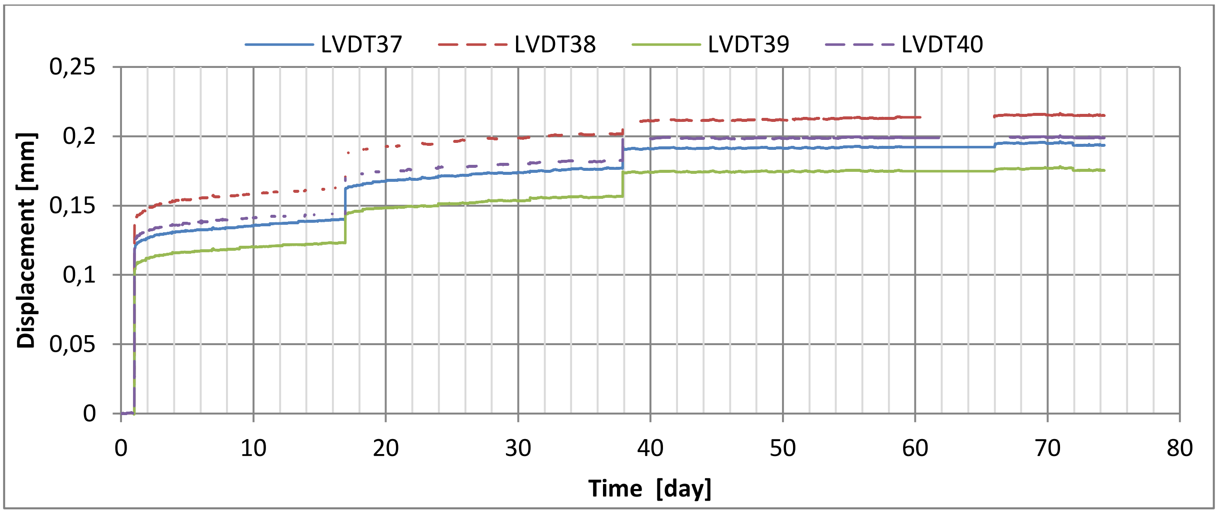


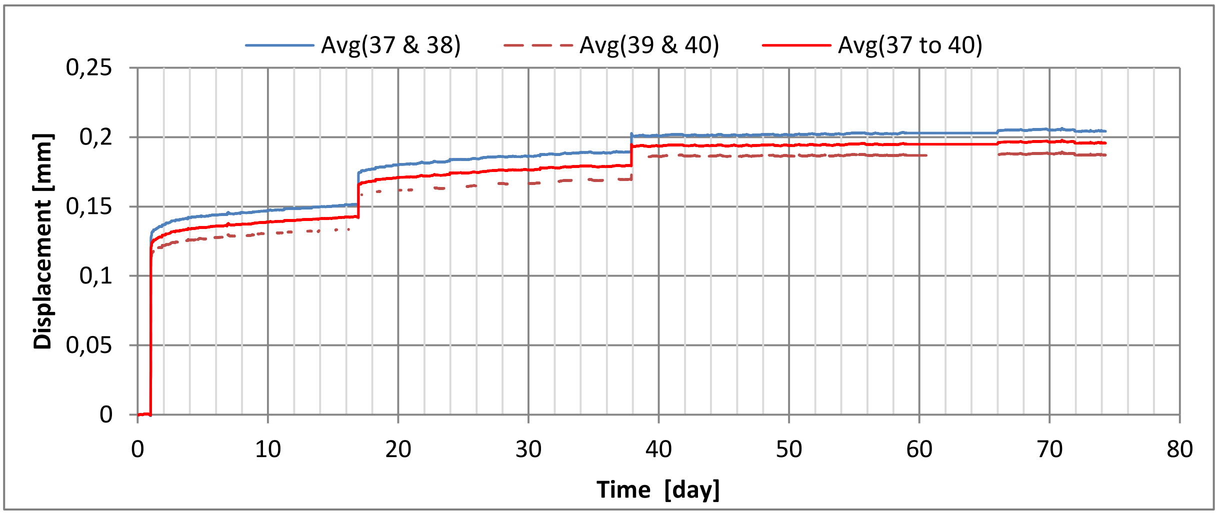
Figure 2.36: Load time history of String 3



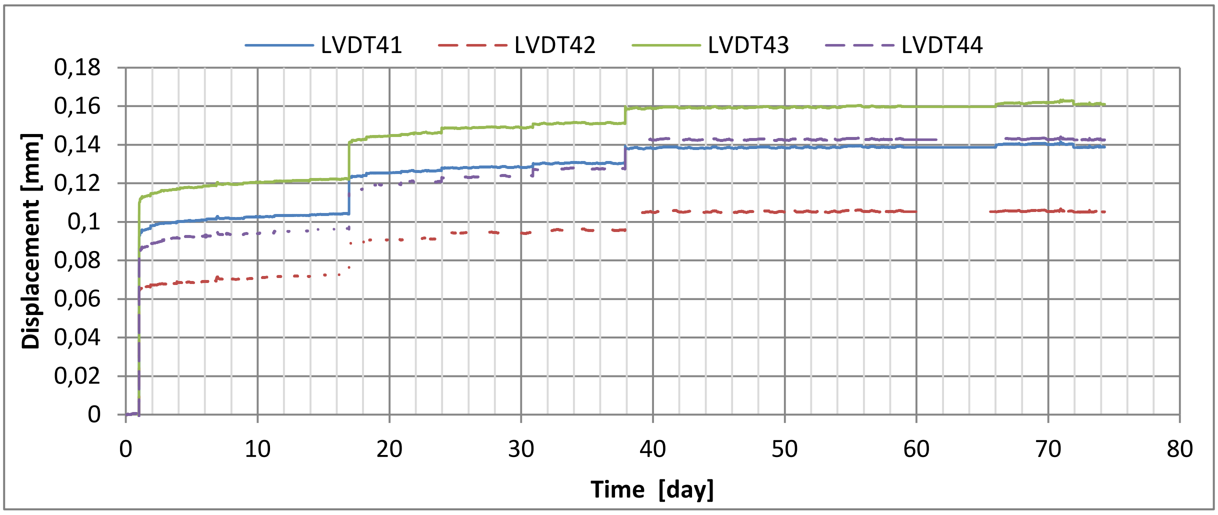


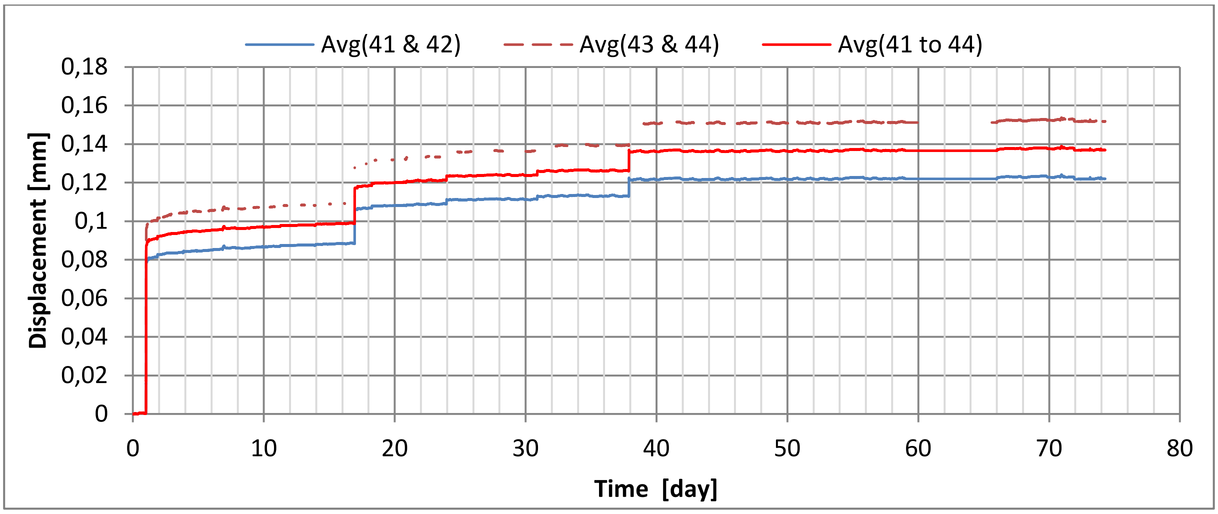
(a) String 3 - 01


LVDT37
LVDT38
LVDT39
LVDT40
Displacement [mm]
0,25
0,2
0,15
0,1
0,05
0
0
10
20
30
40
50
60
70
80
Time [day]

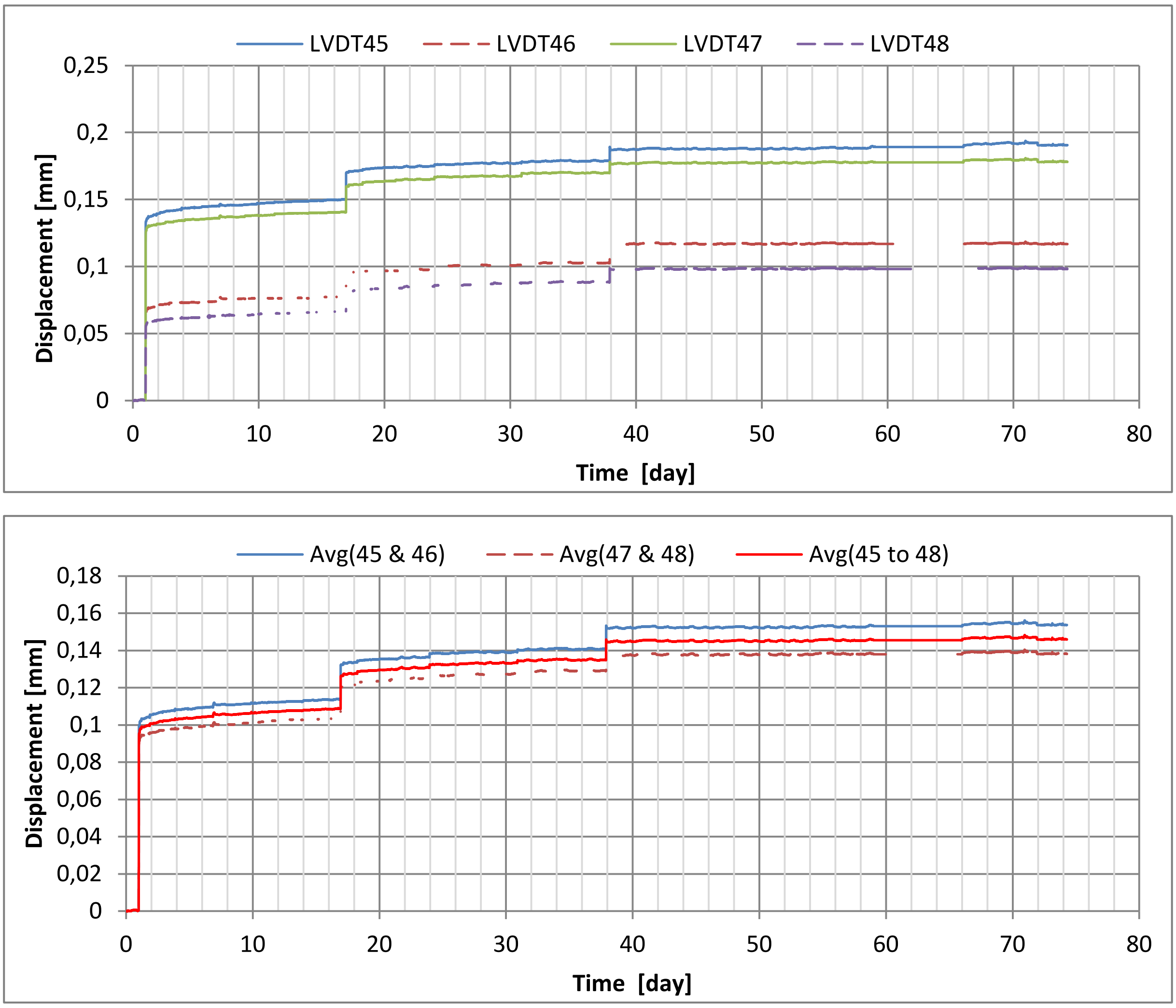

Avg(37 & 38)
Avg(39 & 40)
Avg(37 to 40)
Displacement [mm]
0,25
0,2
0,15
0,1
0,05
0
0
10
20
30
40
50
60
70
80
Time [day]

(b) String 3 - 02


LVDT41
LVDT42
LVDT43
LVDT44
Displacement [mm]
0,18
0,16
0,14
0,12
0,1
0,08
0,06
0,04
0,02
0
0
10
20
30
40
50
60
70
80
Time [day]

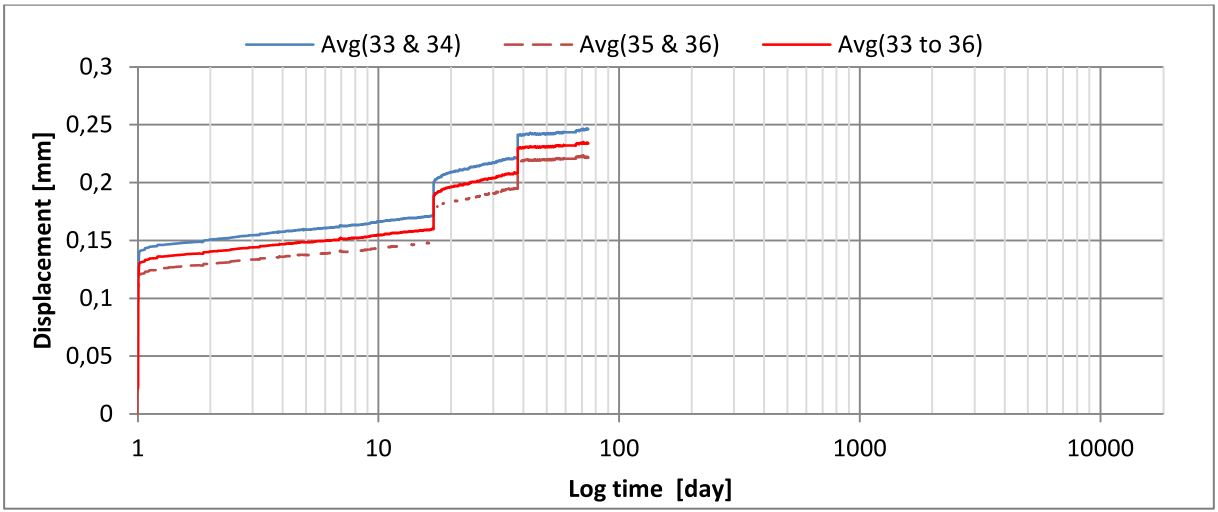


(c) String 3 - 03

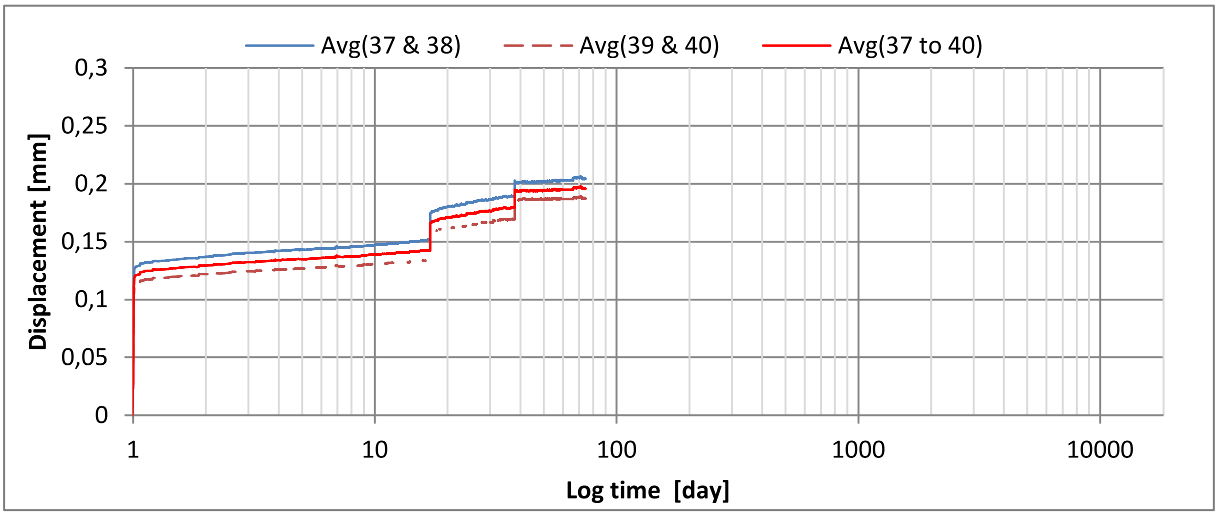


(d) String 3 - 04

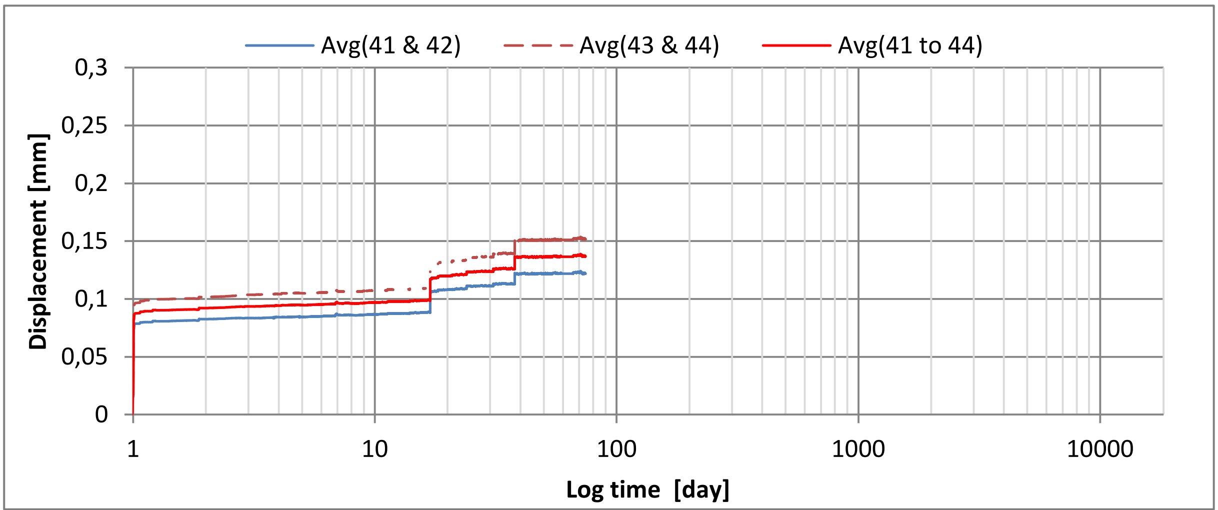
Figure 2.37: Displacement vs time curves of String 3



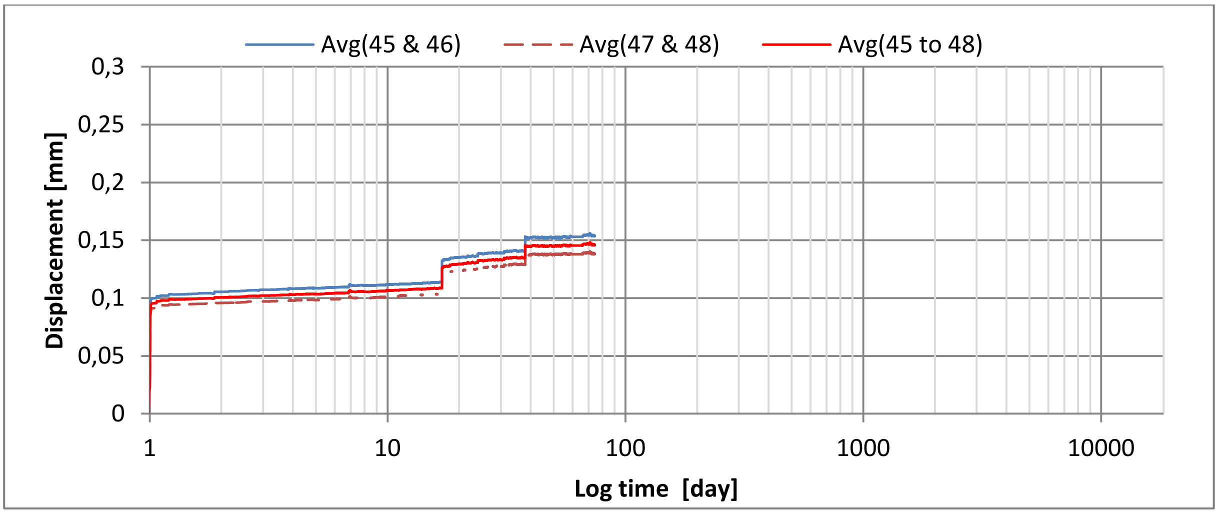
(a) String 3 - 01



(b) String 3 - 02



(c) String 3 - 03



(d) String 3 - 04

Figure 2.38: Displacement vs log time curves of String 3

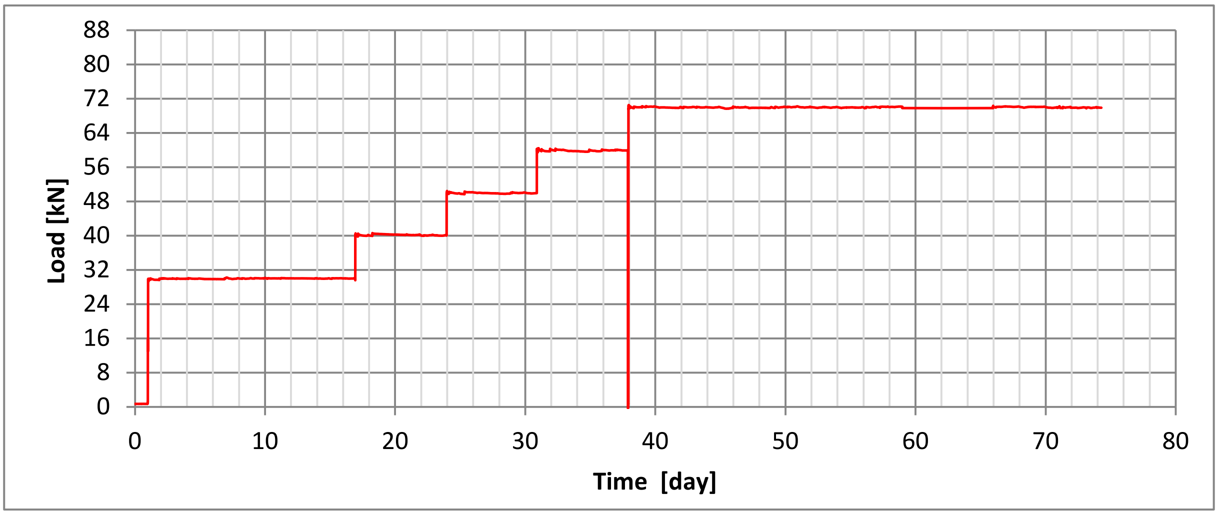
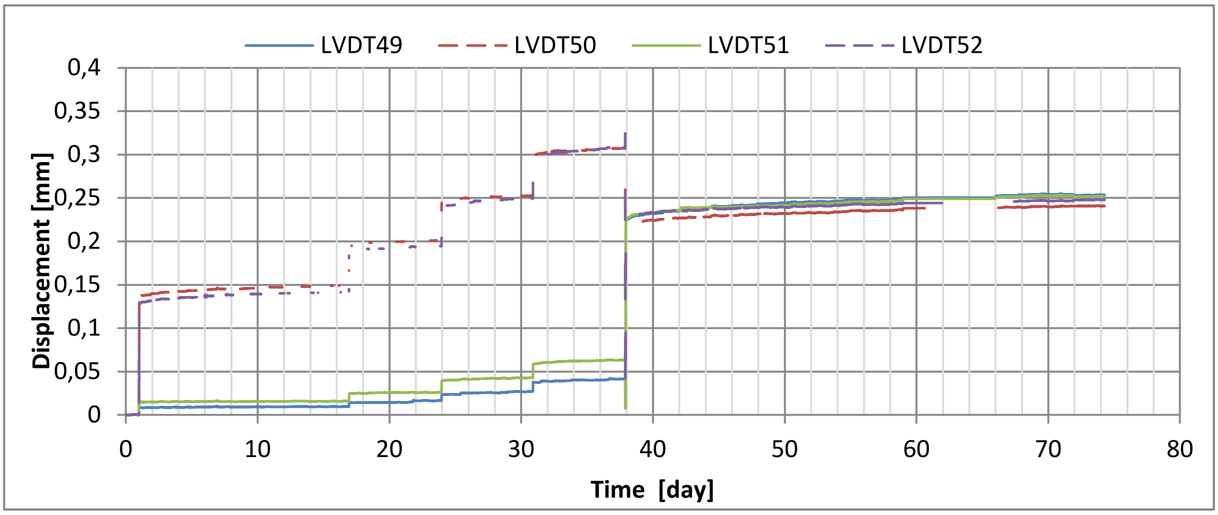
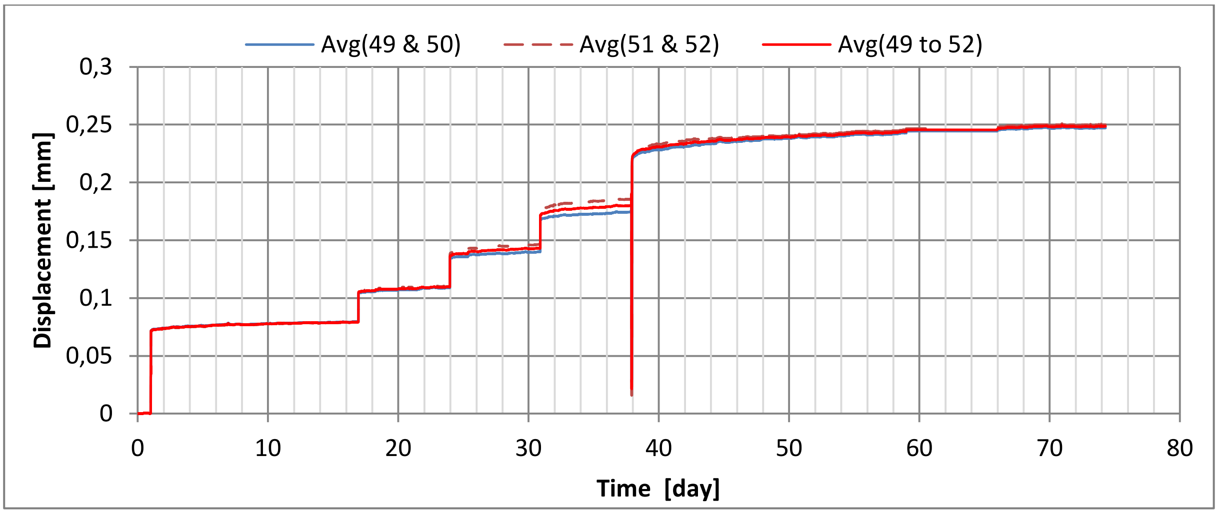
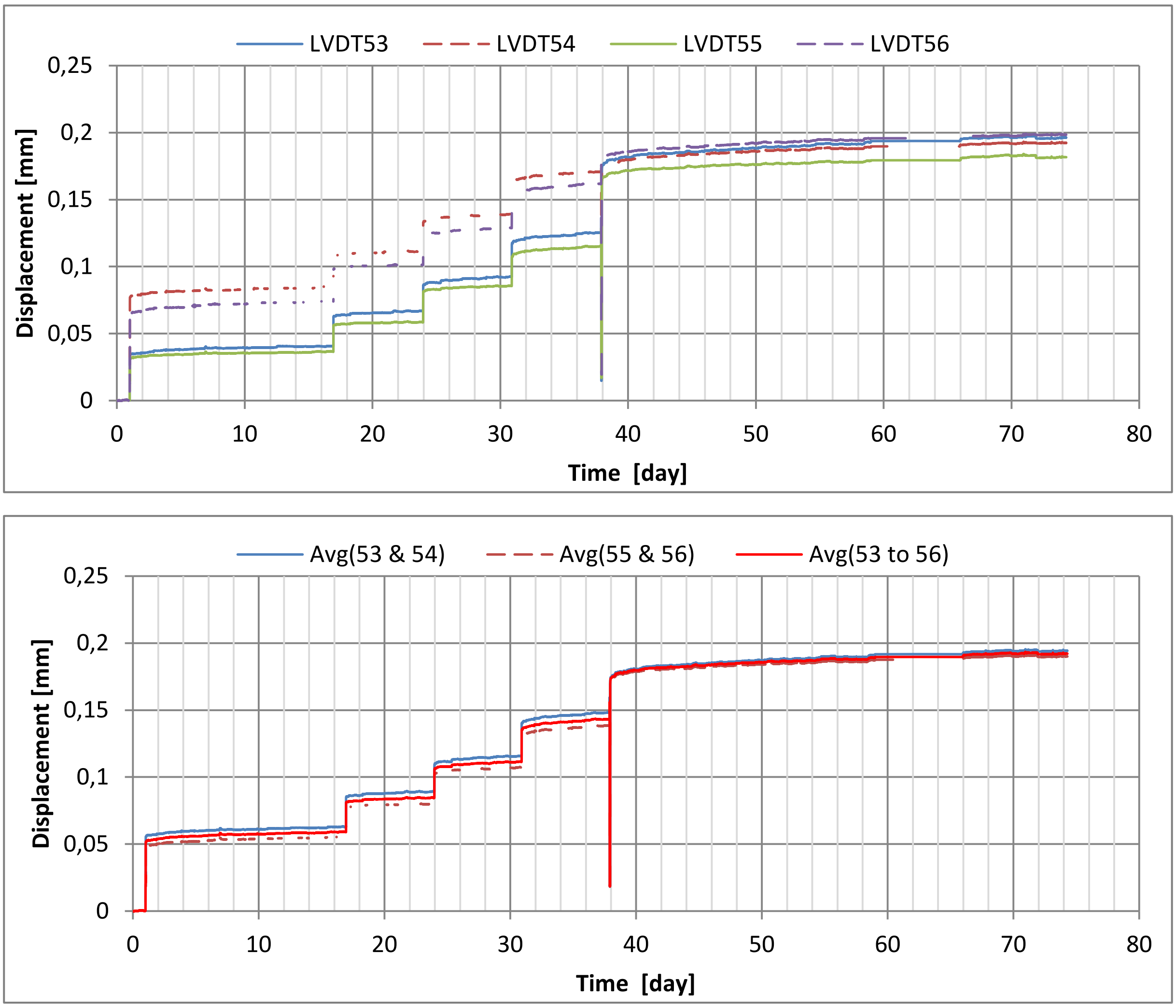


Figure 2.39: Load time history of String 4

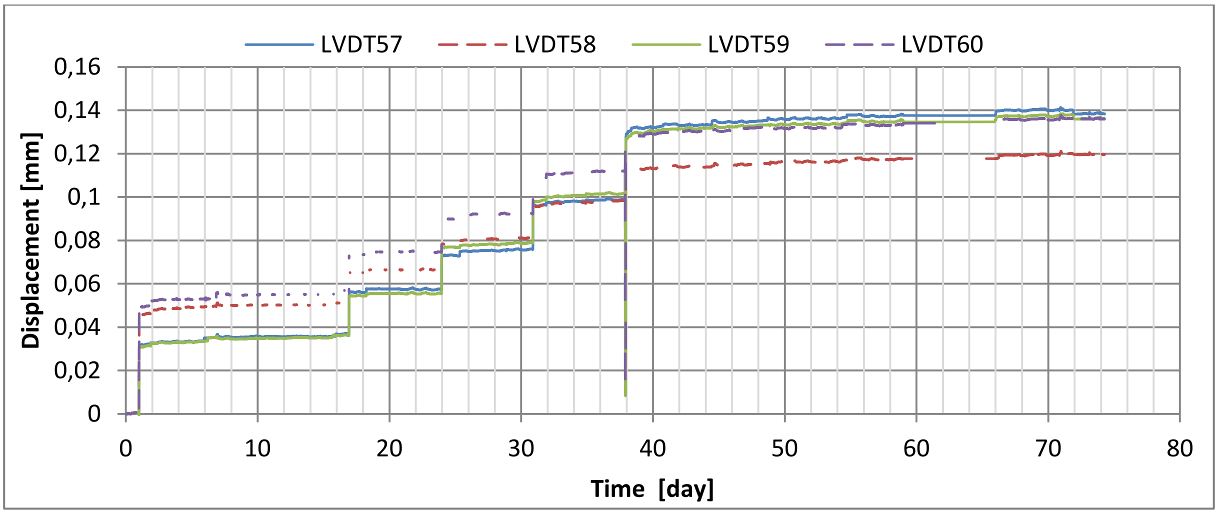


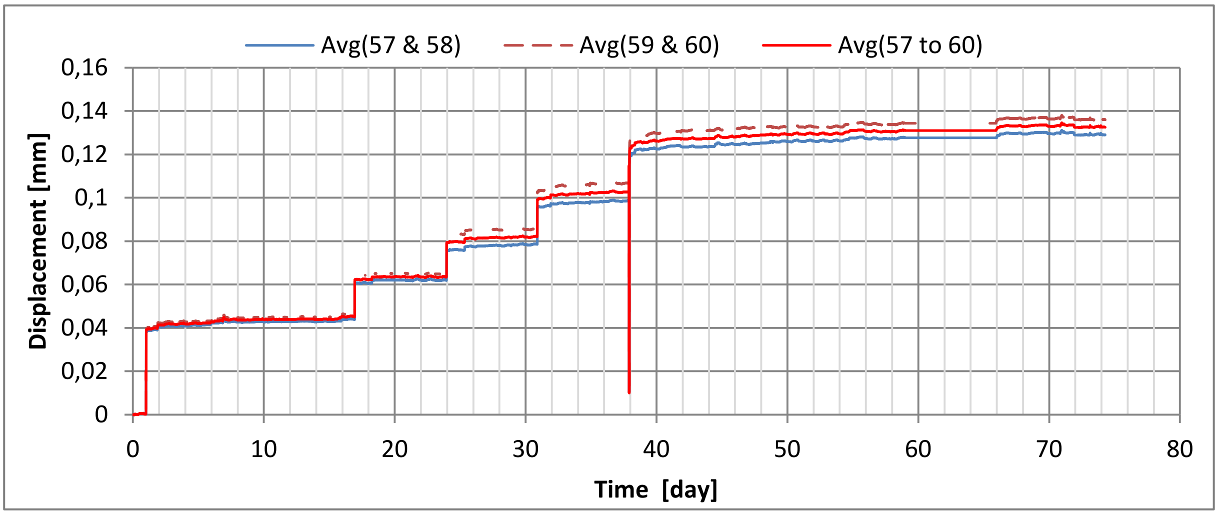


(a) String 4 - 01

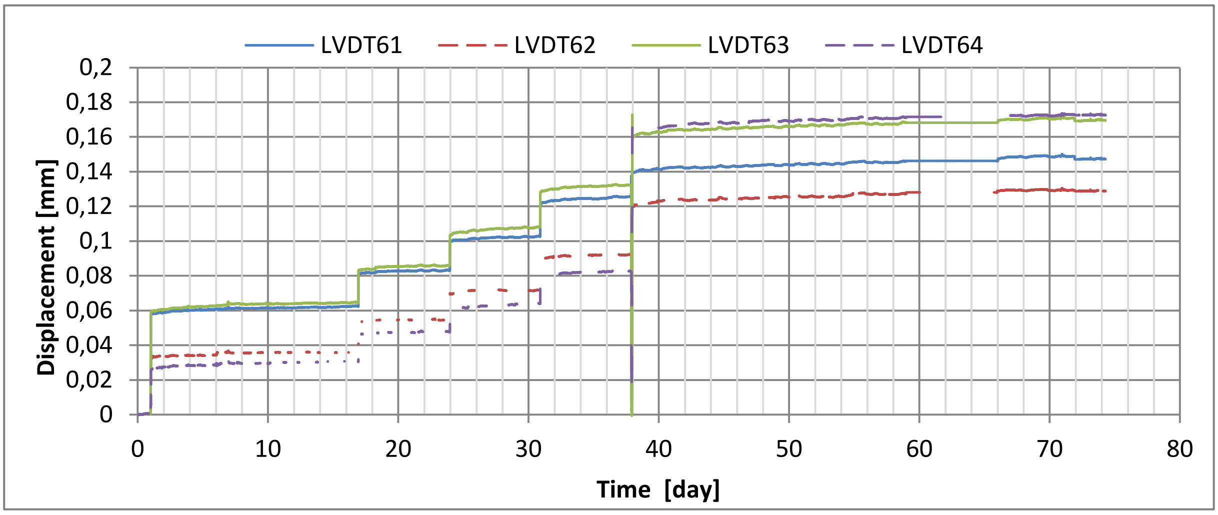


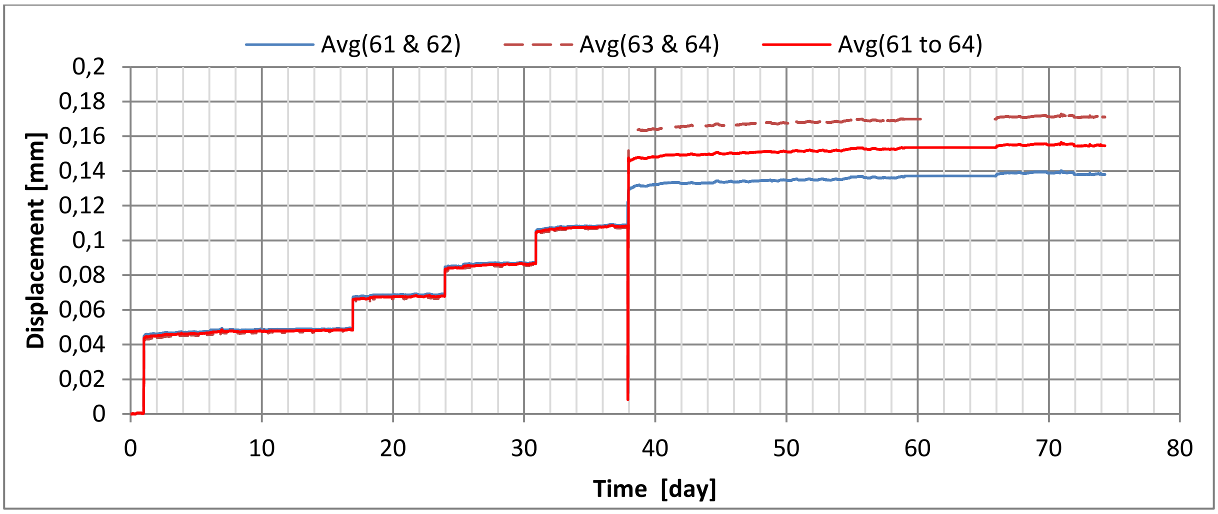
(b) String 4 - 02


LVDT57
LVDT58
LVDT59
LVDT60
Displacement [mm]
Time [day]


Avg(57 & 58)
Avg(59 & 60)
Avg(57 to 60)
Displacement [mm]
Time [day]

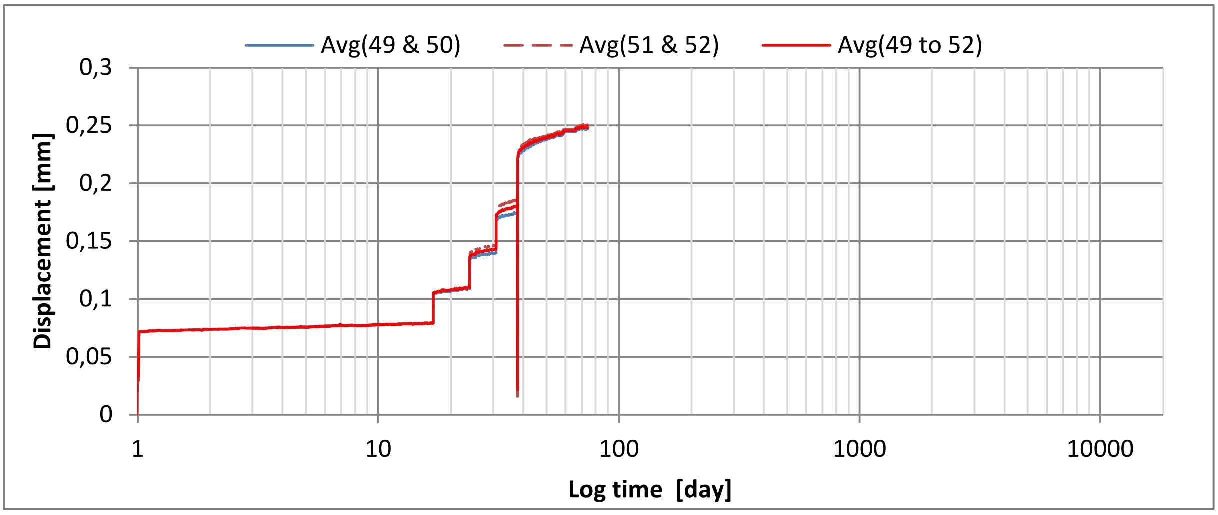
(c) String 4 - 03


LVDT61
LVDT62
LVDT63
LVDT64
Displacement [mm]
Time [day]

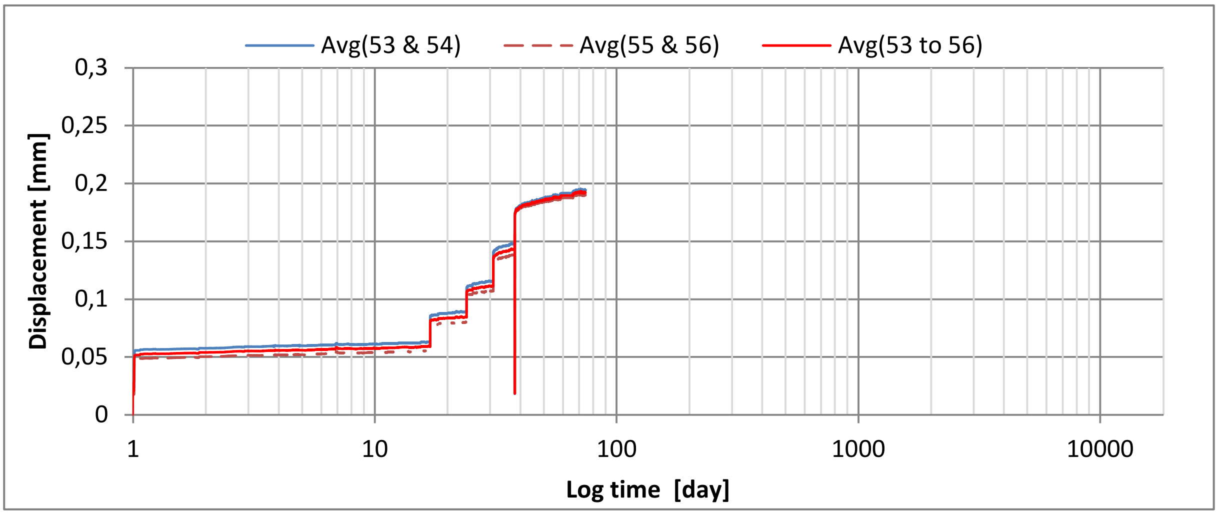


(d) String 4 - 04

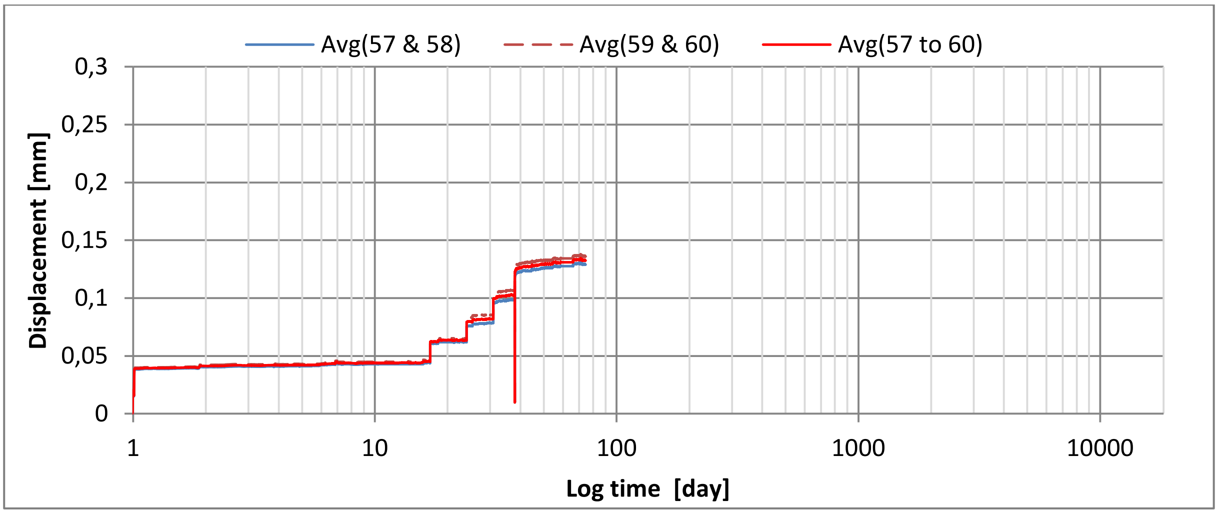
Figure 2.40: Displacement vs time curves of String 4



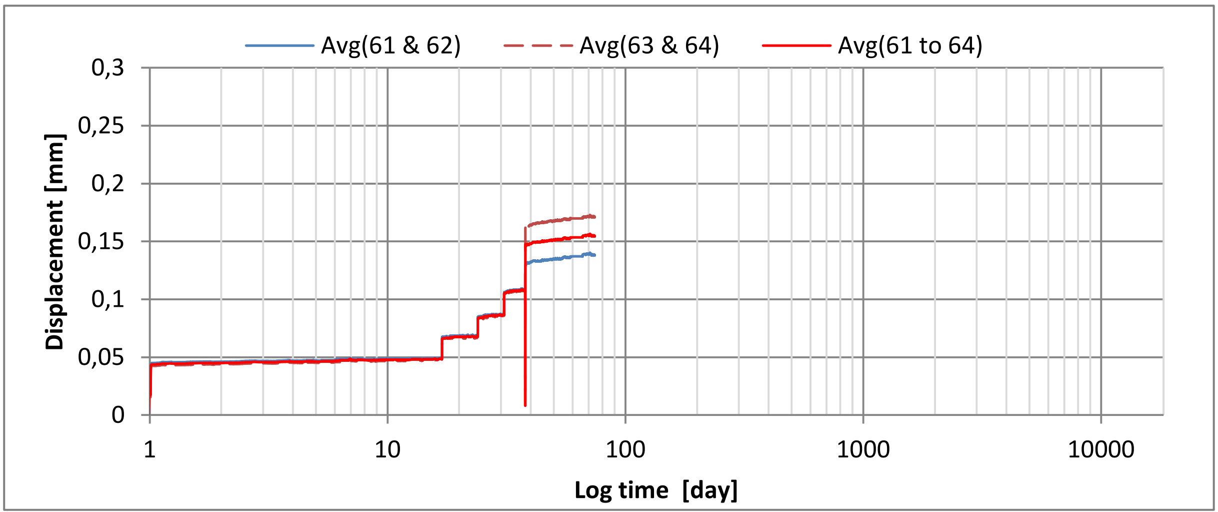
(a) String 4 - 01



(b) String 4 - 02



(c) String 4 - 03



(d) String 4 - 04

Figure 2.41: Displacement vs log time curves of String 4

Based on the displacement-time curves in Figures shown above, the displacements at some selected critical time points of four strings are listed in Table 2.22 to Table 2.25.

The selection principle of critical time points are

- L: time point when the load reaches to the preset load step value
- U: time point just before the string were unloaded
- A: time point when the accident had been happened
- S: supplementary time point between time points above to make a appropriate time interval

The initial capital character represent the type of time point.

Table 2.22: Displacement at critical time points (String 1)

Name of specimen	Time point (days)	Time point type	Force value (kN)	Displacement (mm)					Normalization	Difference (%)
				Lvdt 01/05/ 09/13	Lvdt 02/06/ 10/14	Lvdt 03/07/ 11/15	Lvdt 04/08/ 12/16	Avg. of 4 Lvdt		
String 1 - 01	1	L	48	0.164	0.177	0.240	0.227	**0.202**	1.77	77.4
	10	S	48	0.206	0.219	0.393	0.370	**0.297**	1.92	92.1
	17	L	56	0.234	0.257	0.449	0.422	**0.341**	1.92	92.1
	24	S	56	0.245	0.265	0.486	0.452	**0.362**	1.95	95.1
	31	S	56	0.250	0.275	0.507	0.473	**0.376**	1.98	97.5
	38	A	56	0.256	0.285	0.521	0.487	**0.387**	1.99	99.2
	52	S	56	0.258	0.287	0.544	0.504	**0.398**	2.04	103.7
	66	U	56	0.259	0.288	0.560	0.519	**0.407**	2.07	107.0
String 1 - 02	1	L	48	0.116	0.137	0.110	0.147	**0.128**	1.12	12.2
	10	S	48	0.153	0.179	0.151	0.195	**0.170**	1.10	9.8
	17	L	56	0.177	0.209	0.180	0.224	**0.197**	1.11	11.1
	24	S	56	0.186	0.217	0.189	0.232	**0.206**	1.11	10.9
	31	S	56	0.191	0.224	0.194	0.236	**0.211**	1.11	11.0
	38	A	56	0.197	0.229	0.200	0.241	**0.217**	1.12	11.5
	52	S	56	0.198	0.231	0.203	0.242	**0.219**	1.12	11.8
	66	U	56	0.199	0.232	0.205	0.242	**0.220**	1.12	11.8
String 1 - 03	1	L	48	0.103	0.116	0.115	0.122	**0.114**	1	0
	10	S	48	0.133	0.157	0.163	0.164	**0.155**	1	0
	17	L	56	0.152	0.180	0.191	0.186	**0.177**	1	0
	24	S	56	0.158	0.189	0.202	0.193	**0.186**	1	0
	31	S	56	0.160	0.196	0.208	0.197	**0.190**	1	0
	38	A	56	0.163	0.200	0.213	0.201	**0.194**	1	0
	52	S	56	0.164	0.201	0.214	0.202	**0.195**	1	0
	66	U	56	0.165	0.202	0.216	0.202	**0.196**	1	0
String 1 - 04	1	L	48	0.135	0.186	0.174	0.064	**0.140**	1.23	22.7
	10	S	48	0.168	0.488	0.565	0.123	**0.336**	2.17	117.5
	17	L	56	0.199	0.577	0.632	0.136	**0.386**	2.18	117.7
	24	S	56	0.208	0.657	0.711	0.144	**0.430**	2.31	131.5
	31	S	56	0.216	0.711	0.756	0.148	**0.458**	2.41	140.6
	38	A	56	0.223	0.746	0.788	0.152	**0.477**	2.46	145.6
	52	S	56	0.236	0.801	0.827	0.152	**0.504**	2.58	158.0
	66	U	56	0.246	0.841	0.849	0.153	**0.522**	2.66	165.9

Note: The normalization values and difference are all based on the third specimen.

Table 2.23: Displacement at critical time points (String 2)

Name of specimen	Time point (days)	Time point type	Force value (kN)	Displacement (mm)					Normalization	Difference (%)
				Lvdt 17/21/ 25/29	Lvdt 18/22/ 26/30	Lvdt 19/23/ 27/31	Lvdt 20/24/ 28/32	Avg. of 4 Lvdt		
String 2 - 01	1	L	24	0.076	0.052	0.056	0.077	**0.065**	1.60	60.1
	10	S	24	0.092	0.068	0.073	0.101	**0.084**	1.42	41.5
	17	L	32	0.124	0.091	0.1	0.13	**0.111**	1.39	39.5
	24	L	40	0.154	0.119	0.13	0.162	**0.141**	1.41	40.5
	31	L	48	0.191	0.15	0.164	0.195	**0.175**	1.43	43.1
	38	L+A	56	0.229	0.179	0.194	0.228	**0.208**	1.43	43.1
	52	S	56	0.243	0.193	0.207	0.238	**0.220**	1.45	45.1
	66	U	56	0.243	0.199	0.211	0.241	**0.224**	1.46	45.6
String 2 - 02	1	L	24	0.06	0.054	0.037	0.046	**0.049**	1.21	20.9
	10	S	24	0.074	0.064	0.048	0.059	**0.061**	1.04	3.8
	17	L	32	0.101	0.083	0.071	0.085	**0.085**	1.07	6.6
	24	L	40	0.129	0.109	0.096	0.108	**0.111**	1.10	10.0
	31	L	48	0.157	0.131	0.12	0.13	**0.135**	1.10	10.0
	38	L+A	56	0.189	0.157	0.147	0.155	**0.162**	1.12	11.7
	52	S	56	0.194	0.164	0.15	0.159	**0.167**	1.10	9.9
	66	U	56	0.196	0.166	0.151	0.159	**0.168**	1.09	9.4
String 2 - 03	1	L	24	0.031	0.047	0.026	0.059	**0.041**	1	0
	10	S	24	0.039	0.054	0.053	0.09	**0.059**	1	0
	17	L	32	0.057	0.069	0.075	0.118	**0.080**	1	0
	24	L	40	0.074	0.084	0.099	0.145	**0.101**	1	0
	31	L	48	0.093	0.1	0.121	0.175	**0.122**	1	0
	38	L+A	56	0.114	0.118	0.143	0.205	**0.145**	1	0
	52	S	56	0.118	0.122	0.152	0.215	**0.152**	1	0
	66	U	56	0.119	0.122	0.154	0.219	**0.154**	1	0
String 2 - 04	1	L	24	0.04	0.072	0.028	0.055	**0.049**	1.20	19.6
	10	S	24	0.066	0.107	0.038	0.062	**0.068**	1.16	15.7
	17	L	32	0.089	0.134	0.056	0.079	**0.090**	1.12	12.2
	24	L	40	0.116	0.161	0.071	0.094	**0.111**	1.10	10.0
	31	L	48	0.14	0.19	0.088	0.11	**0.132**	1.08	8.0
	38	L+A	56	0.166	0.218	0.105	0.131	**0.155**	1.07	6.9
	52	S	56	0.175	0.227	0.112	0.135	**0.162**	1.07	6.9
	66	U	56	0.178	0.232	0.114	0.135	**0.165**	1.07	7.3

Note: The normalization values and difference are all based on the third specimen.

String 1 and String 2 were unloaded at the 66th days after loading, see also in Table 2.20. So for these two Strings, the results listed here are also the final results.

Table 2.24: Displacement at critical time points (String 3)

Name of specimen	Time point (days)	Time point type	Force value (kN)	Displacement (mm)					Normalization	Difference (%)
				Lvdt 33/37/ 41/45	Lvdt 34/38/ 42/46	Lvdt 35/39/ 43/47	Lvdt 36/40/ 44/48	Avg. of 4 Lvdt		
String 3 - 01	1	L	60	0.136	0.146	0.127	0.114	**0.131**	1.49	49.5
	10	S	60	0.163	0.170	0.153	0.133	**0.155**	1.60	59.7
	17	L	70	0.200	0.202	0.186	0.167	**0.189**	1.61	61.1
	24	S	70	0.213	0.213	0.198	0.176	**0.200**	1.62	62.2
	31	S	70	0.218	0.219	0.203	0.181	**0.205**	1.63	63.0
	38	A	70	0.241	0.241	0.226	0.210	**0.229**	1.69	68.8
	52	S	70	0.242	0.242	0.227	0.212	**0.231**	1.69	69.3
	74	S	70	0.246	0.246	0.229	0.214	**0.234**	1.71	70.9
String 3 - 02	1	L	60	0.118	0.136	0.103	0.122	**0.120**	1.37	37.1
	10	S	60	0.135	0.159	0.120	0.141	**0.139**	1.43	43.4
	17	L	70	0.163	0.187	0.144	0.171	**0.166**	1.42	41.7
	24	S	70	0.171	0.196	0.151	0.178	**0.174**	1.41	41.1
	31	S	70	0.175	0.200	0.155	0.181	**0.178**	1.41	41.2
	38	A	70	0.191	0.211	0.174	0.198	**0.193**	1.42	42.2
	52	S	70	0.192	0.213	0.175	0.199	**0.194**	1.42	42.5
	74	S	70	0.194	0.215	0.175	0.199	**0.196**	1.43	43.0
String 3 - 03	1	L	60	0.093	0.064	0.110	0.083	**0.087**	1	0
	10	S	60	0.102	0.070	0.120	0.094	**0.097**	1	0
	17	L	70	0.123	0.089	0.141	0.115	**0.117**	1	0
	24	S	70	0.128	0.094	0.149	0.123	**0.123**	1	0
	31	S	70	0.130	0.096	0.151	0.127	**0.126**	1	0
	38	A	70	0.138	0.105	0.159	0.142	**0.136**	1	0
	52	S	70	0.139	0.105	0.159	0.143	**0.136**	1	0
	74	S	70	0.139	0.105	0.161	0.143	**0.137**	1	0
String 3 - 04	1	L	60	0.134	0.066	0.126	0.056	**0.095**	1.09	9.0
	10	S	60	0.147	0.076	0.138	0.065	**0.106**	1.10	10.0
	17	L	70	0.170	0.095	0.160	0.081	**0.126**	1.08	7.8
	24	S	70	0.176	0.101	0.167	0.086	**0.132**	1.07	7.3
	31	S	70	0.178	0.103	0.170	0.088	**0.134**	1.07	6.8
	38	A	70	0.187	0.117	0.176	0.098	**0.145**	1.06	6.3
	52	S	70	0.188	0.117	0.177	0.098	**0.145**	1.06	6.4
	74	S	70	0.191	0.117	0.178	0.098	**0.146**	1.07	6.7

Note: The normalization values and difference are all based on the third specimen.

Table 2.25: Displacement at critical time points (String 4)

Name of specimen	Time point (days)	Time point type	Force value (kN)	Displacement (mm)					Normalization	Difference (%)
				Lvdt 49/53/57/61	Lvdt 50/54/58/62	Lvdt 51/55/59/63	Lvdt 52/56/60/64	Avg. of 4 Lvdt		
String 4 - 01	1	L	30	0.008	0.136	0.015	0.128	**0.072**	1.84	83.7
	10	S	30	0.009	0.147	0.015	0.139	**0.078**	1.77	77.2
	17	L	40	0.014	0.195	0.025	0.188	**0.105**	1.69	69.1
	24	L	50	0.024	0.246	0.040	0.239	**0.137**	1.72	72.2
	31	L	60	0.038	0.300	0.059	0.295	**0.173**	1.73	73.5
	38	L+A	70	0.224	0.218	0.226	0.225	**0.223**	1.82	81.7
	52	S	70	0.246	0.233	0.243	0.241	**0.241**	1.86	86.0
	74	S	70	0.254	0.241	0.252	0.248	**0.249**	1.88	87.5
String 4 - 02	1	L	30	0.034	0.077	0.031	0.064	**0.052**	1.32	32.2
	10	S	30	0.039	0.083	0.035	0.072	**0.057**	1.31	31.0
	17	L	40	0.063	0.108	0.056	0.098	**0.081**	1.31	30.6
	24	L	50	0.087	0.134	0.082	0.124	**0.107**	1.34	34.1
	31	L	60	0.118	0.164	0.109	0.155	**0.136**	1.37	36.9
	38	L+A	70	0.176	0.173	0.166	0.180	**0.174**	1.41	41.5
	52	S	70	0.189	0.187	0.177	0.193	**0.186**	1.44	44.0
	74	S	70	0.196	0.192	0.182	0.198	**0.192**	1.45	44.9
String 4 - 03	1	L	30	0.031	0.045	0.031	0.049	**0.039**	1	0
	10	S	30	0.036	0.050	0.035	0.055	**0.044**	1	0
	17	L	40	0.056	0.065	0.054	0.073	**0.062**	1	0
	24	L	50	0.073	0.078	0.077	0.090	**0.079**	1	0
	31	L	60	0.096	0.096	0.098	0.109	**0.100**	1	0
	38	L+A	70	0.129	0.110	0.127	0.126	**0.123**	1	0
	52	S	70	0.136	0.116	0.134	0.132	**0.129**	1	0
	74	S	70	0.138	0.120	0.136	0.136	**0.133**	1	0
String 4 - 04	1	L	30	0.058	0.032	0.059	0.026	**0.044**	1.12	12.0
	10	S	30	0.061	0.036	0.064	0.030	**0.048**	1.09	8.5
	17	L	40	0.081	0.054	0.083	0.046	**0.066**	1.06	6.0
	24	L	50	0.100	0.070	0.104	0.061	**0.084**	1.05	5.1
	31	L	60	0.122	0.090	0.129	0.080	**0.105**	1.06	5.6
	38	L+A	70	0.139	0.120	0.160	0.164	**0.146**	1.19	18.6
	52	S	70	0.144	0.126	0.167	0.170	**0.152**	1.17	17.1
	74	S	70	0.147	0.129	0.170	0.173	**0.155**	1.17	16.6

Note: The normalization values and difference are all based on the third specimen.

For further comparing the differences between fours specimens in a same string, the average displacements of 4 Lvdts at eight critical loading time points also could be drawn with a histogram, which is shown in Figure 2.42 to Figure 2.45.

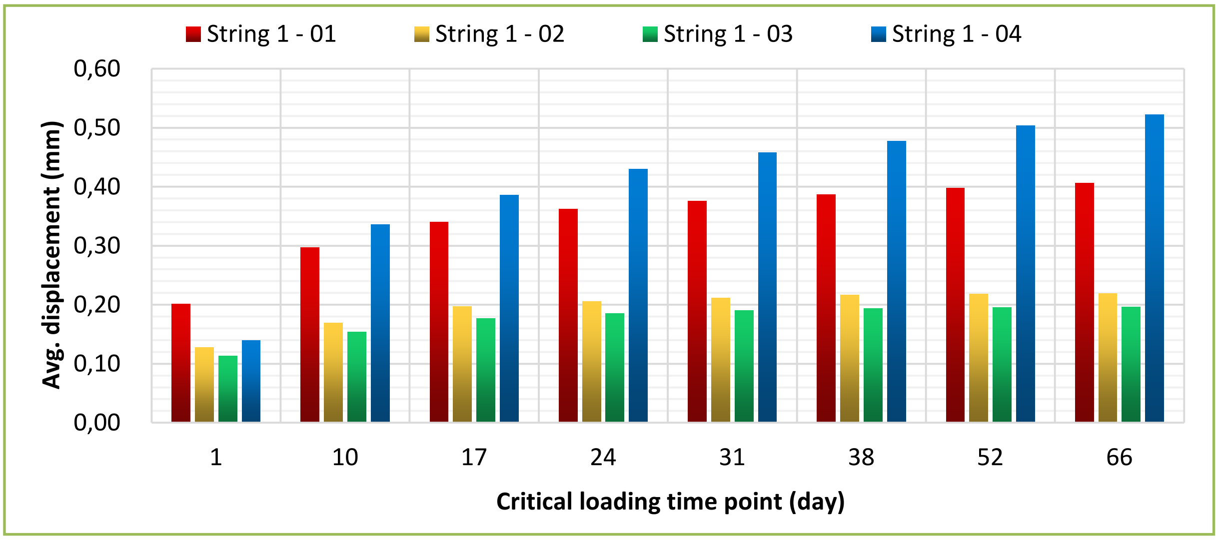


Figure 2.42: Histogram of Avg. displacement at critical time point (String 1)

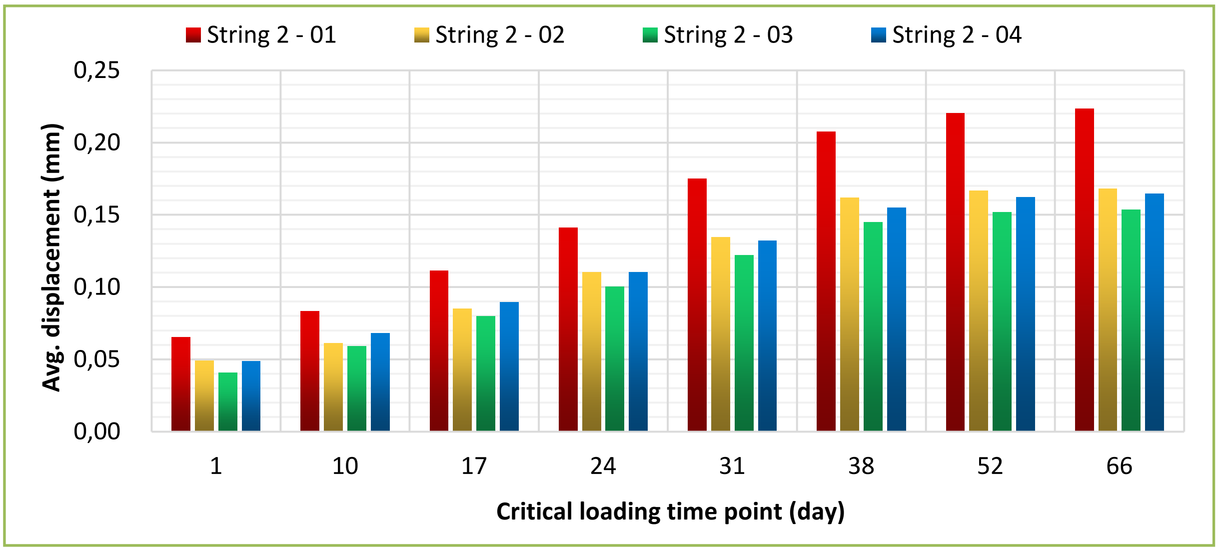


Figure 2.43: Histogram of Avg. displacement at critical time point (String 2)

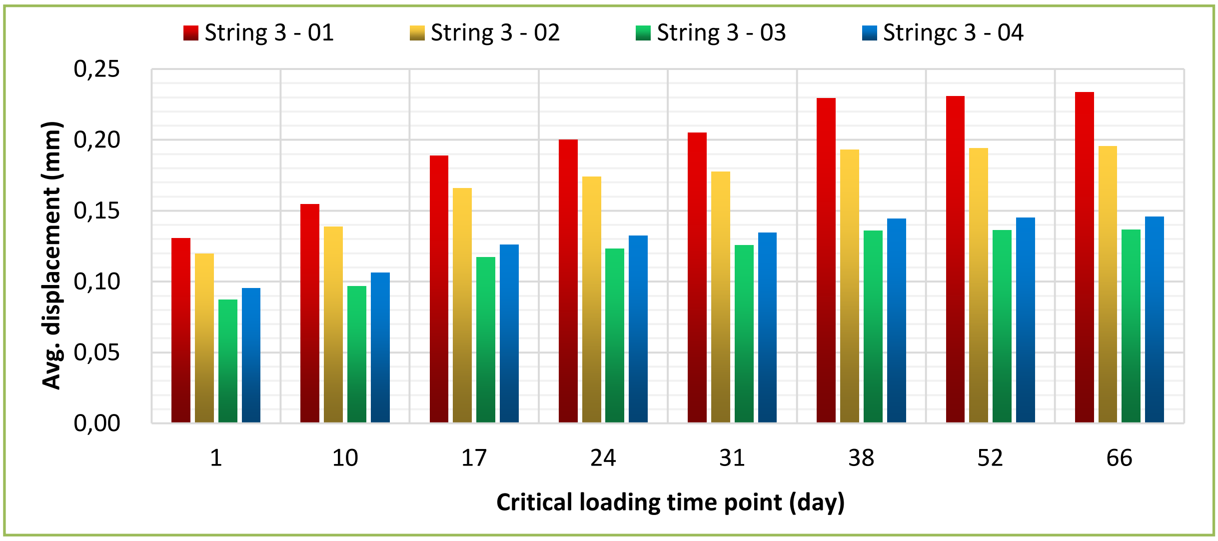


Figure 2.44: Histogram of Avg. displacement at critical time point (String 3)

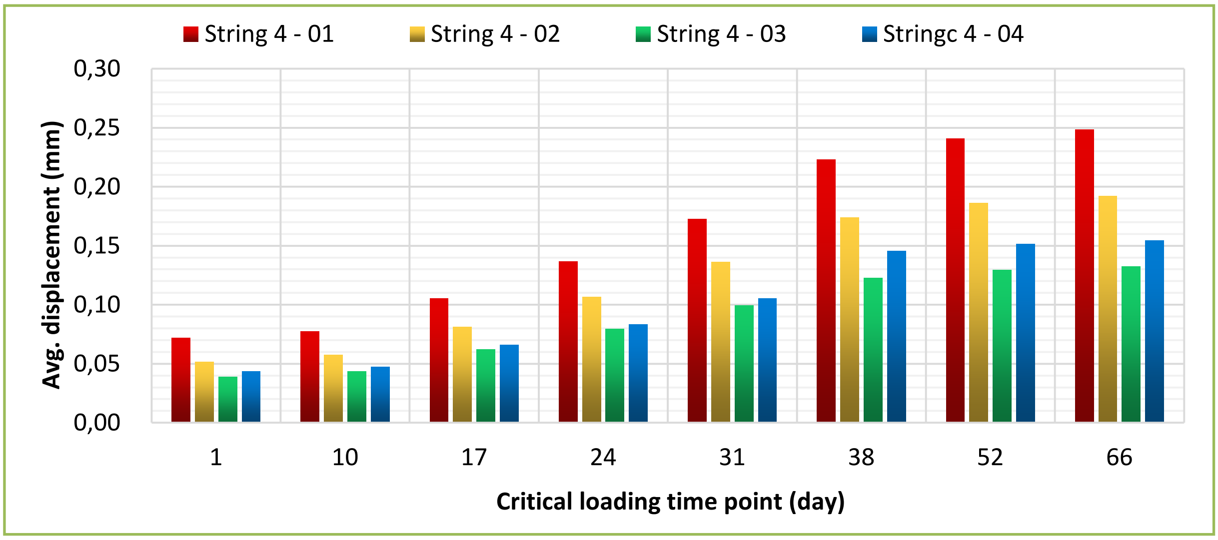


Figure 2.45: Histogram of Avg. displacement at critical time point (String 4)

2.2.3.8 Conclusions

RenGel (Araldite) has shown a good and stable bearing capacity during a loading period of 70 days at a maximim load level of 70% of the benchmark force value of 0.15 mm slip at CBG of the plate as obtained in Step 2. The displacements of the specimens with a normal round hole with 2 mm clearance appeared to around 0.15 mm. The displacements of the specimens with a slotted hole of 4 mm or 6 mm showed a higher value, 0.20 mm respectively 0.25 mm. The two different loading procedures did effect these values.

The potential alternative resin Edilon Dex-R2K showed an unstable bearing capacity. Considerable difference was even found between the two connections of the same specimens. For some specimens, the slip exceeded 0.3 mm at a load level was only 50% of the benchmark force value of 0.15 mm slip at CBG of the plates as obtained in Step 2. Due to the large scatter of results the effect of slotted holes could not be distinguished.

2.3 Conclusions

The main conclusions getting from all the test stages and test steps are listed here again.

Stage 1 - Step 1 Short term test ***- Resin injection***

- Araldite, the initial resin recommended in ECCS(1994), has achieved the highest tensile force value at the slip value of 0.15 mm, that is 214.5 kN at the center of the bolt group (CBG), and it has also shown the best time dependent behaviour in all of the test resins.
- Except Sika injection 451, three other selected resins for alternative, which are Edilon Dex-R2K, Edilon Dex-G20, and Sikadur 30 separately, all show up a good performance on resin injection.

- Edilon Dex-R2K has taken the second place behind Araldite, for this resin the tensile force value at the slip value of 0.15 mm is 183.0 kN at CBG, and its creep behaviour is not so large as well.
- For Edilon Dex-G20, the tensile force value at the slip value of 0.15 mm is 169.5 kN at CBG, and for Sikadur 30, the same type of force value is 171.0 kN, but both of them have a significant creep behaviour.
- Sika injection 451 has not obtained usable results at all and will not be considered in the following researches.

Stage 1 - Step 2 Short term test ***- Resin curing temperature***

- When the curing temperature fall into a range from 8 °C to 24 °C, the very slightly temperature positive dependency can be neglected both for resin Araldite and resin Edilon Dex-R2K.
- Ambient temperature inside of the Stevin Laboratory will be used as the testing condition for the following tests, which would be approximately vary from 16 °C to 24 °C during the subsequent test period.
- The benchmark force value of 0.15 mm slip at CBG of the plates can be taken as **200kN** for resin Araldite.
- The benchmark force value of 0.15 mm slip at CBG of the plates can be taken as **160kN** for resin Edilon Dex-R2K.
- Resin Edilon Dex-G20 and Sikadur 30 cannot be used as an alternative resin due to the low strength values and the large creep behaviour, so these two resins will not be considered at the subsequent test.
- In order to reduce the effects of the friction between plates furthest, 30 Nm torque has been used for pre-tightening. Test procedure has been modified and it will be used as a standard testing procedure in the subsequent test.

Stage 1 - Step 3 Short term test ***- Resin loading delay***

- Once again, Araldite, the initial resin recommended in ECCS(1994), has been shown to have good, stable connection bearing capacity through the creep tests in this step.
- Resin Araldite also has a very slight creep behaviour. When the specimen has been loading over 90 hours, the connection’s slip would be almost keeping invariability. Most of the slip between outer plate and inner plate had been occurred at the first several hours after loading.
- For resin Araldite, the influence caused by different curing time, which are 6 hours and 24 hours adopted in our tests, could be ignored at all.
- On the other side, Edilon Dex-R2K, the potential alternative resin, has been shown to have unstable connection bearing capacity through the creep tests in this step. Test results of connection’s slip value show great difference between different specimens or even between two connections belong to the same specimen.
- For one of the specimen, R2K-24h-2, the slip value even exceed 0.3 mm when loading after 90 hours under constant load. It is worth noting that the load value at constant load is only 80 kN, which is 50 % of the benchmark force value of 0.15 mm slip at CBG of the plates obtained in Step 2.
- In this case, it is difficult to compare the influence of curing time for resin Edilon Dex-R2K. We can simply say that curing time is an unimportant factor for this kinds of resin.

- In the subsequent tests, the influencing parameter for curing time will no longer be considered, but we will keep all the specimen's curing time at least 24 hours after injecting and before loading.

Stage 2 Long term test

- RenGel (Araldite) has shown a good and stable bearing capacity during a loading period of 70 days at a maximim load level of 70% of the benchmark force value of 0.15 mm slip at CBG of the plate as obtained in Step 2. The displacements of the specimens with a normal round hole with 2 mm clearance appeared to around 0.15 mm. The displacements of the specimens with a slotted hole of 4 mm or 6 mm showed a higher value, 0.20 mm respectively 0.25 mm. The two different loading procedures did effect these values.
- The potential alternative resin Edilon Dex-R2K showed an unstable bearing capacity. Considerable difference was even found between the two connections of the same specimens. For some specimens, the slip exceeded 0.3 mm at a load level was only 50% of the benchmark force value of 0.15 mm slip at CBG of the plates as obtained in Step 2. Due to the large scatter of results the effect of slotted holes could not be distinguished.

Appendix A Testing procedure checklist of injection bolts

A.1 Specimen assembly

- Assemble plates in right orientation.
- Check that the hole in the bolt head is correctly open and no debris is inside.
- Place washer with flat side away from bolt head on the bolt.
- Insert bolt into the bolt hole.
- Place washer with groove with flat side facing steel place on opposite end of bolt.
- Place nut on the bolt.
- Push together center plates before tightening bolt.
- Tighten the nuts to 100Nm (note: later changed to 30 Nm due to friction effects).

A.2 Injection

- Make sure the specimen is cleaned by blowing out debris with pressured air before injection.
- Prepare enough resin to fill all 4 bolts in one go, see Table A.1 below.
- Inject the resin until resin is seen coming from the washer on the side of the nut.
- Be careful with applied pressure to prevent resin coming out the wrong side of the injection canister.

Table A.1: Mass of two components of resin before mixture

Resin	Component A	Component B	Mass of Component A (g)	Mass of Component B (g)	Total mass (g)
Araldite	RenGel SW404	RenGel HY2404	120	12	132
Edilon Dex-G20	'Comp 1'	'Comp 2'	100	20	120
Sikadur 30	'Comp 1'	'Comp 2'	81	27	108

Note: Edilon Dex-R2K is a premixed resin using a conjoined twin cylinder, the mixing process is automatic during the injection procedure.

A.3 Testing

- Before testing loosen the nuts of the bolt and retighten them 'hand-tight'.
- Place LVDTs in the brackets according to the marking on the plates.
- Load the specimens in a load controlled test with a ramp of 0.2 kN/s until a displacement at the CBG of both connections of at least 0.2 mm is reached.

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