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INNOVATIVE TESTING MACHINE FOR CREEP TESTS ON A STRUCTURAL SCALE UNDER HIGH CONSTANT LOAD

Christian Bertram[1], Hans Joachim Blaß[1], Philipp Dietsch[1]

ABSTRACT: In multi-story timber buildings using platform framing, most vertical deformations occur at the floor joints. In these areas, the floor and, in the case of timber frame constructions, the top and bottom plates are loaded perpendicular to the grain. The stiffness of the timber members in this direction is considerably low. Moreover, the literature indicates that deformations due to creep are significantly higher in this direction compared to loading parallel to the grain. However, most studies have been conducted on small-scale specimens, as creep test setups for tests on a structural level necessitating high loads are costly and challenging to handle. Towards this objective, a new testing machine was developed that employs the principle of deadweight combined with multiple levers to amplify the load. This machine can provide a high load over a long time with little effort needed to keep the load constant. Factors influencing the consistency of the load were examined to benchmark the developed machine against other available test setups.

KEYWORDS: timber, compression perpendicular to the grain, creep, testing, levers in series

1 INTRODUCTION AND BACKGROUND

In hybrid multi-story timber buildings using platform framing, the long-term deformations in the floor joints become crucial, as the vertical deformations shall be consistent across all building components. Hence, reliable creep factors for compression perpendicular to the grain on the structural level are required. So far, the given creep factors k_{def} in Eurocode 5 [1] do not differentiate between the loading direction. The number of studies focusing on creep under compression perpendicular to the grain is limited [2, 3, 4, 5]. In addition, the creep factors provided in these studies vary significantly due to the different climates and specimen sizes used. Especially in uncontrolled climates, the creep factors increase substantially [2]. An ongoing research project aims to provide creep factors for commonly used construction methods in floor joints of buildings with platform framing. This requires creep tests on a structural level and thus necessitates a test setup that can provide high loads over a long time. The scheduled test program for creep tests comprises different materials, different structural members, and different construction methods and includes the effects of changing climates. Therefore, the need for a cost-effective and reliable test setup for conducting long-term tests for up to several years arose. This paper gives a short overview of common uniaxial creep test setups and presents the design of a new innovative testing machine.

2 COMMON TEST SETUPS FOR CREEP TESTS WITH UNIAXIAL LOADING

For conducting uniaxial creep tests, different test setups are commonly used, such as creep testing rigs with springs, hydraulic creep testing machines, and levers loaded with deadweights.

Testing rigs with springs are widely used for creep tests with concrete [6] and are also applied for long-term tests on timber [2, 7] due to their simple design. However, using springs has two major disadvantages. First, systems with springs are statically indeterminate, meaning that the resulting load depends on the stiffness of the test rig and the specimens themselves, which is mainly determined by the stiffness of the applied springs. When the specimens deform during the test, the load does not remain constant but changes according to this stiffness [8]. For tests with high loads, springs with high stiffness are used accordingly. Furthermore, due to the variable load caused by the deformation of the specimens, the information about the current load during the test is missing. Determining the load from the deformation of the springs might only be applicable for springs with low

[1] Timber Structures and Building Construction, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany,
corresponding author: Christian Bertram, bertram@kit.edu, https://orcid.org/0009-0002-6600-0209; https://orcid.org/0000-0003-3568-8290

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stiffness. Hence, applying a load sensor throughout the testing period is necessary in most cases.

Hydraulic jacks can be used instead of springs to maintain the load. However, it must be ensured that the hydraulic pressure remains constant throughout the entire test duration, which significantly increases the complexity of this system. Hydraulic systems are available on the market that maintain constant pressure using gas pressure accumulators. However, these systems are expensive and can only be used in environments where temperature fluctuations are minimal due to the gas pressure accumulator. Therefore, a climate chamber is necessary to maintain the load constant. Hence, these machines are not suitable for conducting tests in a natural climate. Furthermore, a permanently installed load sensor is necessary for these systems as well.

The first two mentioned types of testing machines are either not capable of keeping a high load constant over time or are expensive and not applicable in natural climates. Another option is using a lever with deadweight. Such a system maintains a constant load but is limited by the maximum load. In the literature review on the testing of timber, the application of levers in series to multiply the resulting load was not found. Nevertheless, researchers in other fields have used systems with multiple levers to study creep in rocks and concrete [9, 10]. However, utilizing such test setups for testing timber under compression perpendicular to the grain, it is anticipated that the deformation of the specimen would lead to a significant rotation of the first lever due to the low stiffness of the specimens in comparison with rock and concrete.

3 DESIGN PROCESS

At the beginning of the design process, the capacity to provide high loads and the ability to keep the load nearly constant over time were specified as main objectives. To meet both requirements, the idea of a testing machine with several levers and deadweight seemed most suitable.

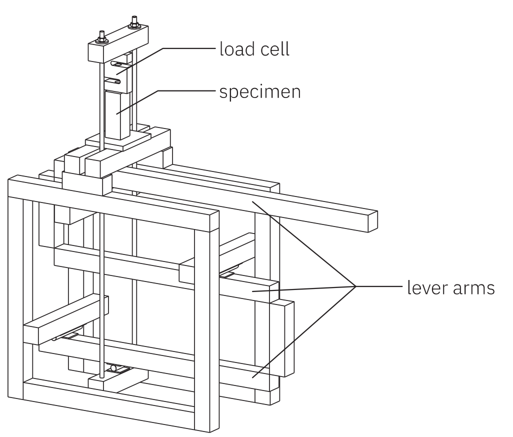
3.1 PROOF OF CONCEPT: BUILDING A SMALL PROTOTYPE

A small prototype with three levers in series, as illustrated in Fig. 1, was built to analyze the feasibility of the multi-lever concept. The horizontally stacked lever arms are pivotally connected by vertical rods, and the reaction forces of the individual levers are internally balanced within the surrounding frame. The resulting load from the third lever is transferred to the top of the frame by two vertical tension rods. To study the behavior, a mass of 1 kg (10 N) was placed at the end of the first lever (see Fig. 1, right). The resulting load was measured to be 770 N. This proved the high potential of the concept. However, a slight difference between the calculated and measured resulting load was observed, likely caused by friction in the hinges. Furthermore, it was found that the amplification of the load is associated with large rotations, particularly of the first lever. Both aspects played a crucial role in the development of the testing machine.

3.2 DESIGN OF A CREEP TESTING MACHINE WITH FOUR LEVERS IN SERIES

Based on the promising results of the prototype, the following key requirements for the machine were defined:

- wide load range of up to 350 kN
- large and freely accessible test space
- height adjustability of the test space
- adjustable load range to be suitable for testing different sizes and materials



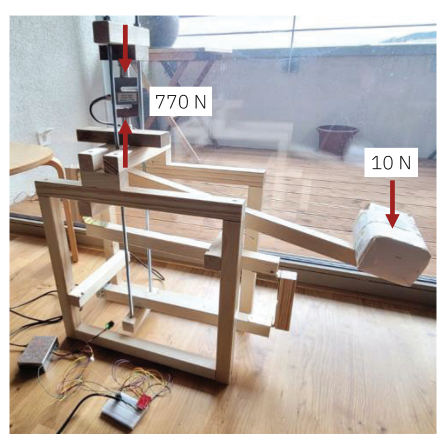


Figure 1: *3D-View of a prototype with three levers (left) and the actual prototype loaded with 10 N (right)*

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- minimized friction in all hinges to keep the load constant
- length adjustability of the connecting parts between each lever to keep them in a nearly horizontal position

The result of the planning process is shown in the left part of Fig. 2. Four levers with different ratios are connected by three tension rods. To reduce the effects of friction, the ends of the tension rods are equipped with rod ends, and the connection from the levers and the vertical U-profiles is done by using radial spherical plain bearings. These bearings are particularly suitable for low sliding speeds in connection with high loads. Furthermore, they are capable of compensating for slight misalignments of the axes, which can occur due to bending.

The area for placing specimens has a total height of about 700 mm and is located at a comfortable working height. It can be freely accessed from both sides of the machine to ensure easy handling for setting up the test and conducting frequent measurements. The location of the supporting base can be vertically adjusted for different specimen heights in steps of 80 mm by the given raster of the vertical U-profiles. A deadweight can be placed on the front of the first lever. The mounting has a shaft diameter of 30 mm, allowing the use of common weights for barbells. Alternatively, a deadweight can also be placed at the end of the first lever. This way, the resulting load from the self-weight of the construction, which is expected to be around 80 kN, can be compensated. This allows to conduct tests with low test loads.

The four levers provide a total ratio of 1:350. When neglecting the self-weight of the construction, this means a deadweight of 100 kg at the first lever results in a testing load of approximately 350 kN. However, there is a significant disadvantage to this high ratio. Not only the load but also the vertical displacement of the lever ends depends on this ratio. This means that a total deformation of the specimens by 1 mm would result in a vertical displacement of the deadweight of 350 mm. For testing materials with high stiffness, this might not pose an issue. However, when considering wood loaded perpendicular to the grain, this ratio becomes challenging. For example, when testing five stacked specimens made of spruce (strength class C24) with a short-term strength of about 3 N/mm², each with a height of 120 mm and a load ratio of 30% of the short-term strength, the vertical displacement u_v of the deadweight would exceed 500 mm due to the elastic deformation at the beginning of the long-term test, as shown in equation (1).

$$u_\mathrm{v} = 350 \cdot \frac{0.3 \cdot 3\,\frac{N}{mm^2} \cdot 5 \cdot 120\;mm}{370\,\frac{N}{mm^2}} = 511\;mm \quad (1)$$

With creep factors for wood loaded perpendicular to the grain of up to 12.5 [2], it becomes evident that a mechanism is needed to readjust the first lever while the test is ongoing. For this reason, two tensioning sleeves are positioned within the third tension rod. With left- and right-hand threads, each sleeve can reduce the length of the tension rod by more than 40 mm. However, these tension sleeves must be unloaded to enable manual adjustment. To achieve this, a pretensioning system commonly used for tension rod systems can be employed. The ability to reduce the length of the third tension rod

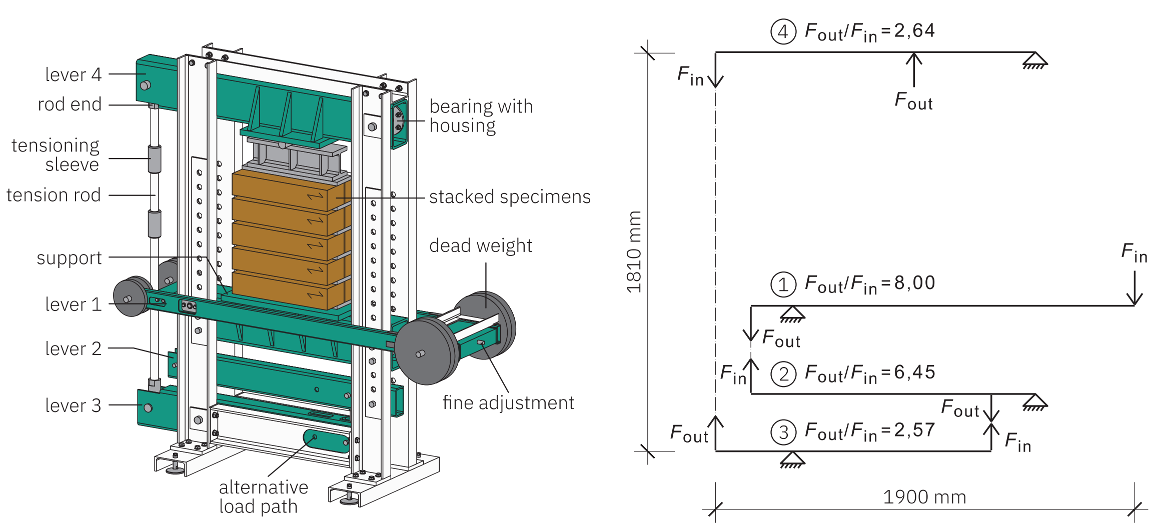

Figure 2: *Final design of the developed creep testing machine (left) and the corresponding schematic sketch of the simplified mechanics (right)*

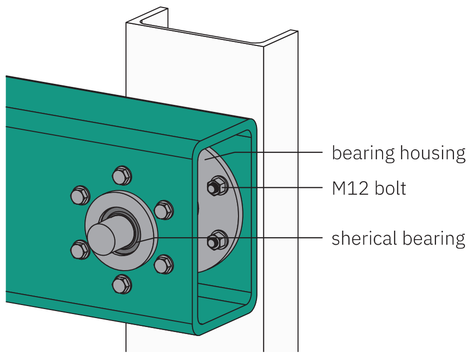

Figure 3: *Connection of the levers to the frame using spherical bearings*

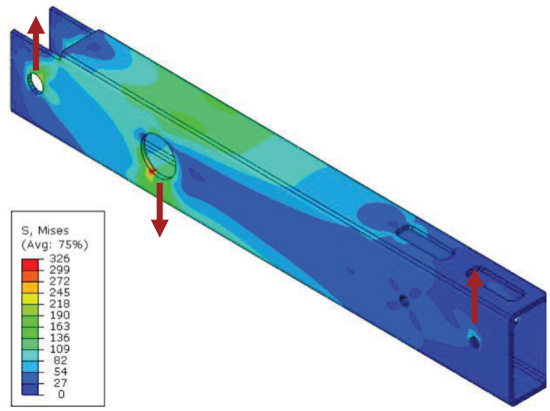

Figure 4: *Finite Element Analysis of the third lever*

by about 80 mm ensures that a total vertical deformation of the specimens of about 30 mm can be compensated. Additionally, the first two tension rods are left- and right-hand threaded at their ends to provide more flexibility when setting up the test.

When low test loads are required, the high ratio may still pose a challenge. In this case, the testing machine offers the option to adjust the ratio of the second and third lever by shifting the position of the second tension rod by 200 mm, resulting in an alternative load path (see Fig. 2). The total ratio is then reduced by about 50%.

3.3 DESIGN OF THE MACHINE ELEMENTS

The cross sections of the levers were initially chosen based on basic beam statics (see Fig. 2, right). This was followed by an extensive iterative process aimed at finding an optimal balance between the load-bearing capacity and the material usage while always considering the kinematics. Using steel profiles with a rectangular hollow section (RHS) for the levers appeared to be the most practical choice, as the rod ends could simply be positioned on axes at the center of the section. To connect the levers to the tension rods, only a small part of the web needs to be milled, along with the holes for the axes of the rod ends and the bearing housings. The axes of the bearings turned out to be the bottleneck in terms of structural design due to high bending and shear stresses. To minimize friction in the hinges, the diameter of the axes should be as small as possible. The width of the RHS determines the bending stress on the axes. Therefore, narrow profiles are preferable. However, the profile height should not be too large, as this would either make the testing machine too tall or reduce the available height of the test chamber. To minimize the bending stress on the axes connecting the frame to the levers, the horizontal distance between the vertical U-profiles was kept to a minimum, determined by the width of the widest RHS of the testing machine. To keep the axes' diameter small, they were made from high-strength steel of type 42CrMo4.

The spherical bearings are mounted in bearing housings (see Fig. 3), which are attached to the lever with six screws each. This way, the load is transferred through both direct contact and the screw connection, ensuring a high load-bearing capacity. The rod ends were selected based on the diameters of the axes and, in turn, determine the diameters of the tension rods. Due to the thin webs of the vertical U-profiles, 10 mm thick reinforcement plates were structurally incorporated.

Throughout the entire design process, priority was given to working primarily with standardized materials and components to minimize effort and costs. In this regard, bolted connections were preferred over welds wherever possible and practical. This also significantly simplifies both the assembly and transportation of the machine.

For the design of the levers, a finite element analysis was conducted separately for each lever to identify the highest stress concentrations in the profiles. The analysis was based on a load of 1 kN applied to the first lever. The resulting stresses for the third lever are shown as an example in Fig. 4. Steel of strength class S355 was used for all levers and the frame.

To precisely adjust the load, the deadweights are mounted on a sliding carriage that can be moved horizontally, allowing control over the static length of the first lever. Due to the high ratio, even slight shifts cause significant load changes, necessitating the implementation of a fine adjustment mechanism. The position of the deadweight can be finely adjusted using a knurled screw.

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To monitor the load during testing, strain gauges will be applied to the third tensile rod. These gauges, along with an additional temperature and humidity sensor, will be continuously monitored using a low-cost microcontroller [11, 12].

3.4 PRETEST OF THE LENGTH-ADJUSTING SYSTEM

Before manufacturing the machine, the mechanism for shortening the third tension rod under load was tested. For this purpose, the tension rod – consisting of three rods and two tensioning sleeves – was placed in a uniaxial testing machine. The machine was set to apply a tensile load of 150 kN and then maintain it at a constant level. The pretensioning system was subsequently installed. The corresponding experimental setup is shown in Fig. 5.

Using two hydraulic pistons and a pump, the load can be transferred from the tensioning sleeve to the tension rods of the pretensioning system. Once the load is fully transferred, the tensioning sleeve can be slightly turned to reduce the length, causing a slight decrease in the load within the pretensioning system. After each adjustment, the load in the pretensioning system must be reset to match the load in the tension rod before further adjustments can be made.

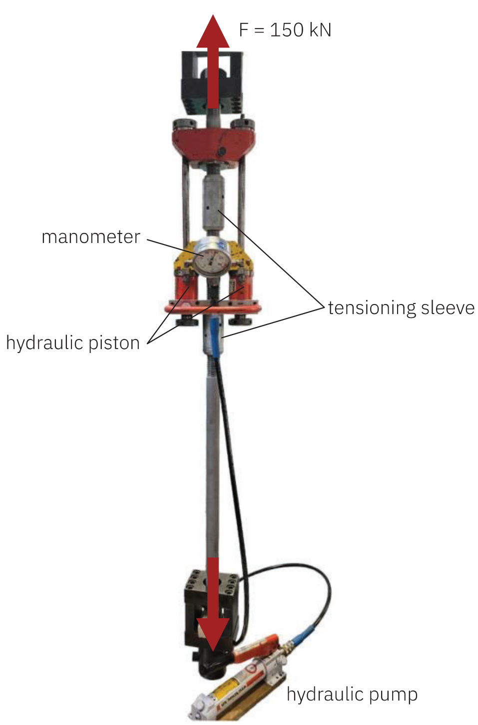

Figure 5: *Tension rod with pretensioning system installed*

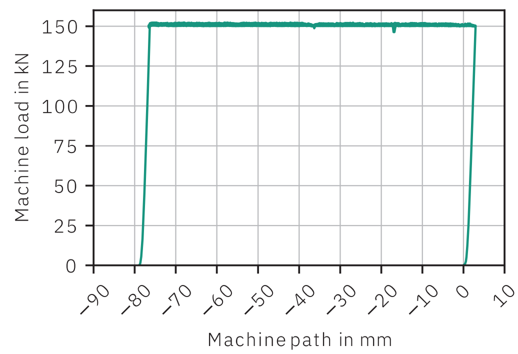

Figure 6: *Load-displacement curve showing constant load while shortening*

With the two tensioning sleeves, it is possible to reduce the length of the rod by about 80 mm. The full process of reducing the length can be seen in Fig. 6. Following an initial elongation of the rod from elastic deformation, the length decreases while the load remains nearly constant. During this process, the pretensioning system had to be disassembled once and reassembled on the second tensioning sleeve. After achieving the full shortening of approximately 80 mm, the tension rod was unloaded. The test demonstrated that the pretensioning system is well-suited for use in the testing machine. The pretensioning system itself consists mostly of standardized parts, making it possible to design a simplified pretensioning system specifically for this testing machine.

4 LOAD CONSISTENCY

The key requirement for a creep testing machine is its ability to maintain a constant load throughout testing. Therefore, factors that may affect load consistency were further analyzed.

Two factors were identified that could influence load consistency. First, the hinges between the levers and the tension rods, as well as those between the levers and the frame, are not entirely free of friction. When the specimen's height is reduced due to creep or a reduced moisture content, all levers will rotate slightly. Occurring friction in the hinges would prevent a free rotation and, thus, the load on the specimen would drop slightly. The opposite would happen when the specimen's height increases, for example, due to a higher moisture content overnight in a natural environment.

The friction of each hinge depends on the coefficient of friction (COF) and the radius of the roller diameter. However, determining specific COFs is complex as they vary, for example, with the applied normal force [13, 14]. The values provided by the manufacturer of the utilized

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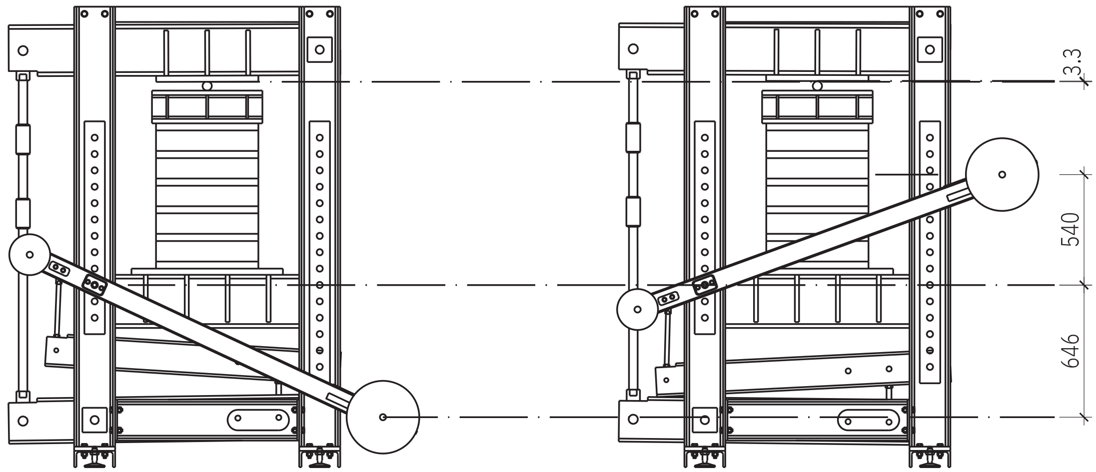

Figure 7: *Kinematics of the levers: minimum (left) and maximum (right) positions of the first lever*

bearings range from 0.02 to 0.25 [15]. Therefore, the COFs could only be roughly estimated. For this study, a value of 0.1 was assumed. The normal force for each bearing was calculated based on a deadweight of 1 kN at the first lever. These parameters were used to calculate the frictional moments at each hinge. In a structural analysis, these moments were applied at each hinge in the opposite direction of rotation, and the resulting load at the location of the specimens was calculated. Compared to the resulting load with a deadweight of 1 kN, this leads to an influence of about 6%.

Another factor influencing the resulting load of the machine is the inclination of the levers under load. Fig. 7 shows the maximum possible rotations of all levers and the corresponding range of vertical displacement at the load application point at the end of the first lever. It becomes evident that, in particular, the rotation of the first lever arm is not negligible. To study this effect, a structural analysis using third-order theory, which takes large deformations into account, was performed. By specifying different contractions for the third tension rod, three geometric variations were examined. As a reference, the contraction was adjusted so that the first lever was horizontal. The result of this adjustment is equivalent to a calculation using first-order theory. Subsequently, calculations were performed with the first lever at its lowest and highest possible positions under load. The results of all three calculations are presented in Fig. 8. It shows that the maximum deviation between the highest and lowest positions of the first lever is approximately 2%.

5 CONCLUSION AND OUTLOOK

To obtain reliable creep factors for the design of timber structures, creep tests on a structural level with high constant loads are essential. While existing test setups may be suitable for testing materials with high stiffness, their application for testing timber in compression perpendicular to the grain is questionable. Therefore, a universal testing machine capable of conducting creep tests with high loads was developed. Using the concept of multiple levers in series allows for high loads but results in significant rotations, particularly of the first

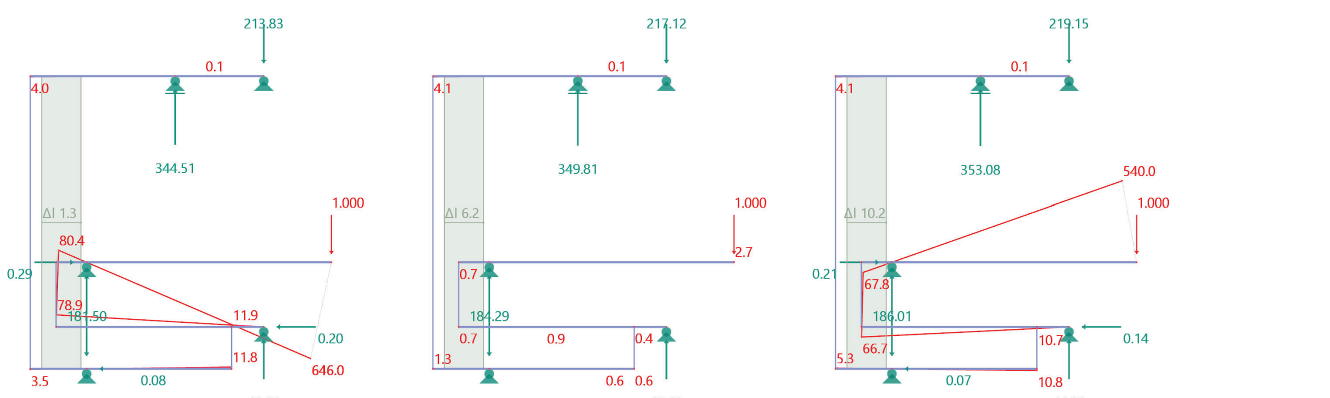

Figure 8: *Calculations using 3rd order theory: Analysing the influence of the inclination of the levers*

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lever. This limitation was addressed by using a pretensioning system to shorten one of the connecting tension rods between the levers. Two load-influencing factors were identified: friction at the hinges and the effects of third-order theory in combination with different positions of the first lever. The error due to friction was estimated to be around 6%. This effect will be further analyzed once the first testing machine is built, which may reveal a smaller error in practice. The error due to third-order effects is comparatively small and can almost be eliminated by ensuring the first lever remains horizontal using the pretensioning system. The developed machine can be used to test materials with low stiffness and is also well-suited for testing materials with high stiffness. In these cases, the rotation of the levers becomes a minor issue, as the deformations of the specimens will be minimal.

The results of the analysis of the final machine will be published in a future paper.

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