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BENDING TESTS OF VERY THICK PLATES WITH ADVANCED RESEARCH EQUIPMENT AND TECHNIQUES

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ABSTRACT

The “ultimate bending machine” was built on the basis of a hydroforming machine located on Tornio campus of Lapland University of Applied Sciences. Applying the machine for bending tests was engineered and implemented in cooperation with SSAB and special tools were designed and constructed for the tests. The maximum force of the press is 30 000 kN, which makes it possible to bend even 80-mm-thick plates.

With the press, bendability tests were carried out for 40-80-mm-thick steels. The test setup included an infrared camera which was used in order to record the increase in the temperature of the plate. The influence of the forming speed on the temperature changes was studied as well. In some of the tests, the spring-back was also measured using video camera recording. The quality of the bends was evaluated by visual inspection and the minimum bending radius of each material was determined.

A demonstration with the online optical strain analysis tool GOM ARAMIS was also carried out. A steel plate was bent and the strains were measured through a mirror below the bending sample. A rectangular hollow section beam was also bent in the press and the strains were measured directly with the same optical strain analysis system. The results of the tests were encouraging and there are plans to apply the method in further studies.

INTRODUCTION

The usability of ultra-high-strength and wear-resistant steels has been studied for several years at Lapland University of Applied Sciences. Bendability tests have been carried out by using a commercial press brake and research techniques have been developed in cooperation with SSAB and the University of Oulu. In the bendability tests, the minimum bending radius (R_{min}) of the material, i.e. the smallest radius which is able to be used without failures, is usually defined. The result of the test is evaluated by means of visual inspection. The spring-back which usually takes place in three-point bending is measured with video camera recording.

As the strength and thickness of the steels being tested are increasing all the time, the demand for more powerful forming machines has arisen. At the beginning of the millennium, a hydroforming press was delivered to the VTT Technical Research Centre of Finland from Russia. Later on, the ownership of the machine was transferred to the Vocational College Lappia, which is a partner cooperating with Lapland University of Applied Sciences. The maximum force of the main cylinder is 30,000 kN, and the maximum pressure in hydroforming is 5000 bars. With the press, the aim was originally to research the hydroforming of tubes and sheets. However, it has mainly been used for traditional forming such as deep drawing and stretch forming. At the MetNet seminar in Aarhus, the idea of using the press for bending tests was proposed [Toppila et al. 2011]. In cooperation with SSAB, the design and construction of the necessary special tools were started.

Previously, bent samples were studied with the GOM ARGUS 3D optical strain analysis system in order to get more detailed information about the metallurgical phenomena involved in bending [Arola et al. 2015, Ruoppa et al. 2014]. In this technique, a grid is marked on the surface of the unbent sample. After bending, on the basis of the change in the grid, a computer system calculates the strain distribution on the surface. In addition to ARGUS, the GOM system also has another optical strain measurement system called ARAMIS, which is able to measure strains online during the bending process. The system is based on marking of the stochastic pattern on the surface and its changes during plastic deformation. By using this technique, more information is expected from the process.

MODIFICATION OF THE HYDROFORMING PRESS FOR BENDING TESTS

The basis of the design for the lower tool was that the die gap should be adjustable. The ultimate force of the press is 30,000 kN, which was set as the basis for the strength calculations. Figure 1a shows a 3D model of the tool. The tool was designed to consist of two halves which were constructed by welding from 40- and 60-mm UHS steel cuttings with a nominal yield strength of 960 N/mm^2. The halves are assembled on top of T-slot plates and move towards and away from each other when the bolts are not tightened. The die gap varies from 100 to 800 mm. The strength of the tools was analyzed with FEM modelling using the maximum force of the machine. The stresses are shown in Figure 1b. It can be seen that the tools take the maximum force, with the maximum stresses being clearly below the strength of the material.

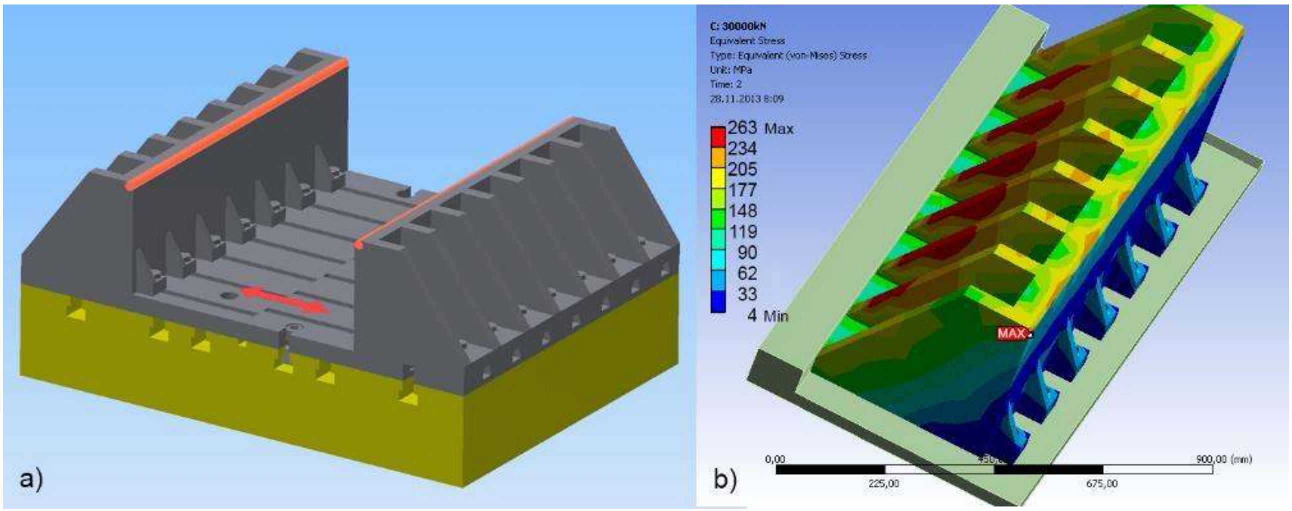

Figure 1. a) 3D model of the lower tool; b) stresses calculated by FEM in half of the lower tool with the maximum load of the press being used

Figure 2a shows the hydroforming machine on the Tornio campus. The diameter of the main cylinder is about 1000 mm and the stroke of the piston is 500 mm. For the attachment of the punches, a beam was constructed from 60-mm-thick steel plate and it was fastened to the bed in the head of the piston. The press also has two side cylinders on both sides of the frame which are used for moving the tools in order to adjust the gap of the lower tool. The cylinders also support the lower tool during the bending, thus resisting the horizontal forces which tend to separate the halves away from each other'.

Figure 2. a) Hydroforming machine on the Tornio campus; b) bending of a thick steel plate

In the press, the speed of the punch is adjustable and it is possible to record data such as the displacement and pressure of the cylinder. With this press and tool setup, it was now possible to bend even 80-mm-thick UHS steel plates.

FIRST BENDING TESTS OF THICK PLATES

The first bending tests for thick plates were carried out with the press above. The materials were SSAB's 50-mm Strenx 700, 45-mm Raex 400 and 450, and 80-mm S355, the typical mechanical properties of which are shown in Table 1.

Table 1. Typical mechanical properties of the test materials

Test material	$Rp_{0,2}$ N/mm^2	R_m N/mm^2	A_5 %
S355	355	500	23
Strenx 700	700	850	12
Raex 400	1000	1250	10
Raex 450	1250	1450	9

Samples were cut from the sheets so that the bending line was either longitudinal or transverse vs. the rolling direction (RD). With the 45- and 50-mm thicknesses, the bending length was 400 mm and with the 80-mm thickness, it was 600 mm. The die gap was set to be suitable for each case, taking into account the strength and thickness of the material and the punch radius used. The speed of the punch was in most cases 1.5 mm/s, which is, in practice, the maximum speed for bending tests carried out with the ultimate press. However, some tests were carried out with a lower speed, 0.2 mm/s, in order to study the influence of the speed on the bendability.

Since the deformation of the material elevates the temperature, it may become significant for the forming properties, and this was also studied. For the measurement of the surface temperature, an infrared camera was assembled in front of the machine and placed sloping downwards towards the bending sample. Figure 3a shows the positioning of the camera and Figure 3b an example of the temperature measurement during the bending test.

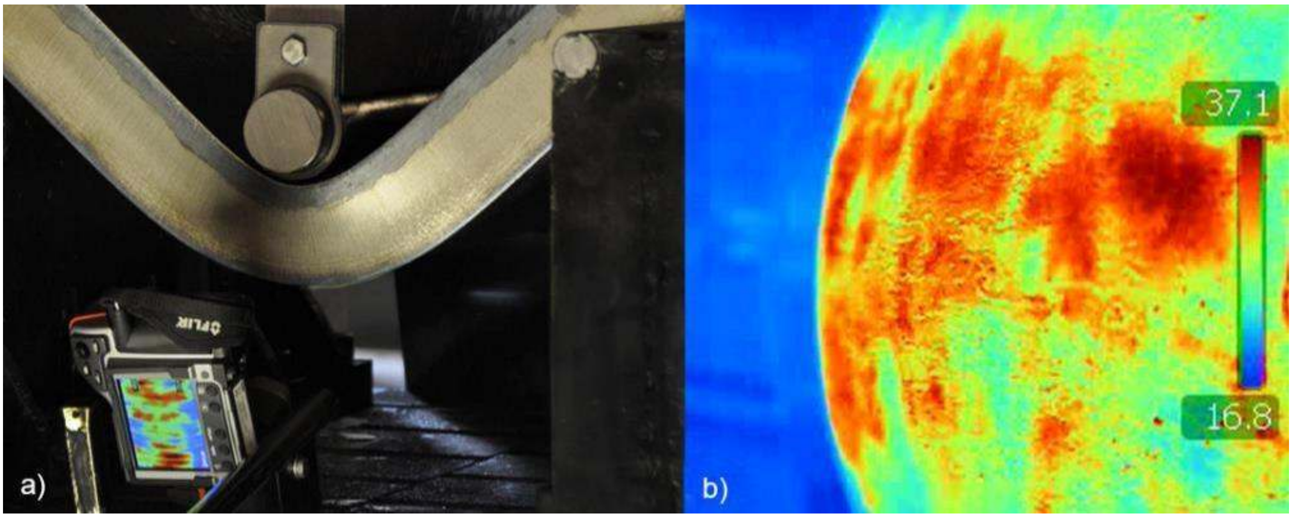

Figure 3. a) Bending of 80-mm S355, position of infrared camera; b) example of temperature measurement in bending test of Raex 400

The results of the bending tests are shown in Table 2. The minimum bending radius relative to thickness R/t was determined for each material and the average maximum temperatures recorded in the bending tests are also shown in the table.

Table 2. Results of the bending tests

Material	Thickn. [mm]	Punch speed [mm/s]	Bending line vs. RD	Min. bending rad. [R/t]	T_{max} [°C]
S355	80	1.5	Longitudinal	0.4	55
S355	80	1.5	Transverse	0.4	55
S355	80	0.2	Longitudinal	0.4	35
S355	80	0.2	Transverse	0.4	35
Strenx 700	50	1.5	Longitudinal	1.5	38
Strenx 700	50	1.5	Transverse	1.5	38
Strenx 700	50	0.2	Longitudinal	1.5	27
Strenx 700	50	0.2	Transverse	1.5	27
Raex 400	45	1.5	Longitudinal	3.6	38
Raex 400	45	1.5	Transverse	2.9	38
Raex 400	45	0.2	Longitudinal	3.8	31
Raex 400	45	0.2	Transverse	2.9	31
Raex 450	45	1.5	Longitudinal	4.2	38
Raex 450	45	1.5	Transverse	3.6	38
Raex 450	45	0.2	Longitudinal	4.2	31
Raex 450	45	0.2	Transverse	4.0	31

During the tests, it was evident that different steel grades showed different behaviour especially when too small a punch radius was used. Raex 400 and 450 showed a severe cracking tendency when too small a radius was used, while Strenx 700 showed slightly smaller cracks and an interesting phenomenon was also seen in the vicinity of the crack (the formation of ”valleys”). In general, the greater the strength of the steel, the greater the minimum bending radius and, especially with greater strength, usually greater in the longitudinal direction, as shown in Table 2 with Raex steels. It was found that the minimum bending radii R/t are in good agreement with the guaranteed values of thinner plates and the SSAB bending recommendations can also be used for the thicknesses under study.

One primary conclusion is that a faster bending speed leads to higher temperatures during bending. The biggest difference was seen in the thickest test samples (S355, 80mm). It is possible that thicker gauges are more prone to a temperature increase when the punch speed is increased. The peak temperatures in the vicinity of the cracks were 40-116°C. The speed may have some influence on the minimum bending radius at least Raex 450 in the longitudinal direction showed a tendency to crack with a greater punch radius when the speed was 0.2 mm/s.

The maximum bending force was measured in some tests by recording the pressure during the test. For the evaluation of the force, some equations have been published previously:

$$F = \left(0.5 + \frac{4 \times t}{W}\right) \times \frac{b \times R_m \times t^2}{W-(1.5 \times R_p)} \quad (1) \qquad \text{[Ruoppa et al. 2014]}$$

$$F = \frac{b \times R_m \times t^2}{(W-R_d-R_p)} \quad (2) \qquad \text{[SSAB 2015]}$$

where: R_m is the ultimate tensile strength (N/mm^2)
b is the bending length (mm)
t is the sheet thickness (mm)
W is the die gap (mm)
R_d is the die entry diameter (mm)
R_p is the punch radius (mm)

The forces calculated with Equations 1 and 2 were compared with the measured forces and the correlations between them are illustrated in Figures 4a and 4b. The data which Equation 1 is based on includes plate thicknesses from about 4 to 20 mm, leading to much lower forces. The graph shows that Equation 1 is also still quite reliable also greater thicknesses and forces. Equation 2 seems to be a little more accurate with lower forces but with greater forces it deviates more from the measured values than Equation 1. However, both equations can be used for the evaluation of the force needed before bending.

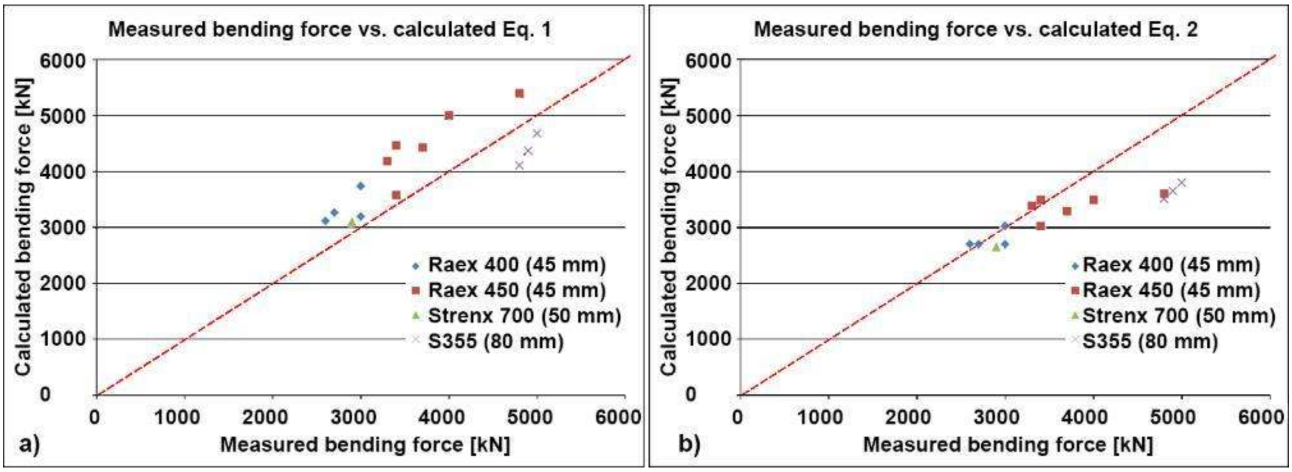

Figure 4. Measured vs. calculated force: a) Equation 1, b) Equation 2

In three-point bending, spring-back typically takes place. After the punch is released, the angle of the plate opens as a result of the elastic deformation, which is, in addition to plastic deformation, always present during bending. It is important to know the amount of the spring-back in the bending process in order to reach correct dimensions in the final part. The spring-back was measured by using a video camera. Two images are sampled from the video, one from the lower end of the punch and another after the release of the punch; see the photographs in Figure 5a. The spring-back angle is measured from the difference between the angles detected from the images.

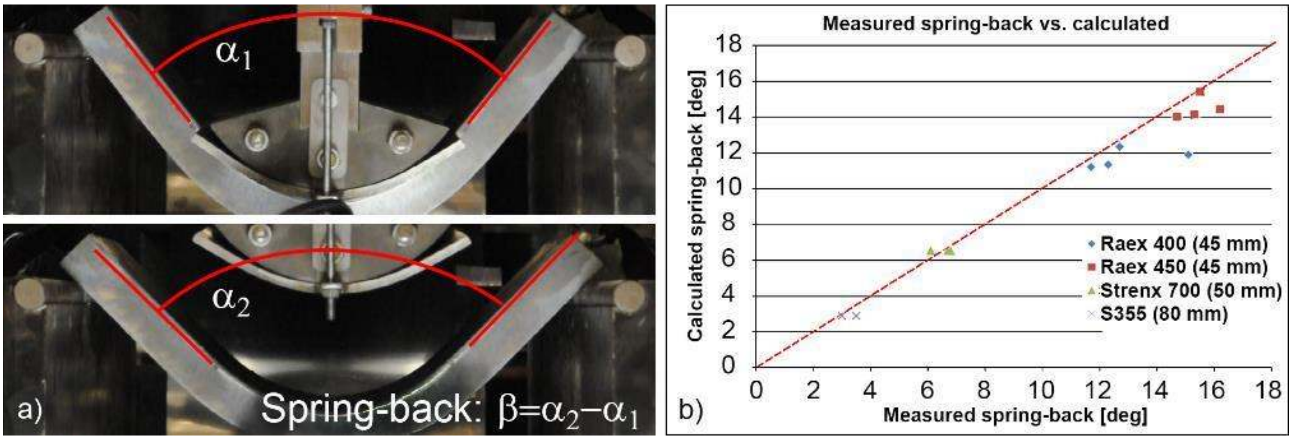

Figure 5. a) Principle of spring-back measurement, b) measured vs. calculated spring-back

For the evaluation of the spring-back, the following equation exists:

$$\beta = C \times \left(\frac{R_e}{990.65}\right) \times \left(\frac{W}{t}\right) \quad (3) \quad \text{[Mäkikangas 2013]}$$

where: R_e is the yield strength (N/mm^2)
t is the sheet thickness (mm)
W is the die gap (mm)
C is the constant (C=1.00 with W/t<25, C=1.10 with W/t≥25)

The spring-back was measured in some tests. In Figure 5b, the correlation between the measured and calculated spring-back is illustrated. This equation was based upon data where the thicknesses were relatively small, but from Figure 5b it can be concluded that the equation also works with greater thicknesses, as tested in this study.

DEMONSTRATION OF ARAMIS ONLINE OPTICAL STRAIN ANALYSIS

Lapland University of Applied Sciences has an optical strain analysis system, GOM ARGUS and ARAMIS, which is a non-contact optical 3D deformation measuring system which analyzes, calculates and documents deformations. ARAMIS recognizes the surface structure of the measuring object in digital camera images and allocates coordinates to the image pixels. During the deformation of the measuring object, further images are recorded. Then ARAMIS compares the digital images and calculates the displacement and the deformation of the object characteristics. ARAMIS is particularly suitable for three-dimensional deformation measurements under static and dynamic loads in order to analyze the deformations and strain of real components.

Before a test can be performed, ARAMIS must be calibrated to ensure the dimensional consistency of the measuring system. During the calibration, the sensor configuration is determined. This means that the distance of the cameras and the orientation of the cameras with regard to each other are determined. In addition, the image characteristics of the lenses are determined (e.g. focus, lens distortions). [ARAMIS manual 2008]

The GOM ARAMIS system was tested in the online measurement of strain during bending tests. Cameras were fixed directly to the bending machine in a vertical position, as shown in Figure 6.

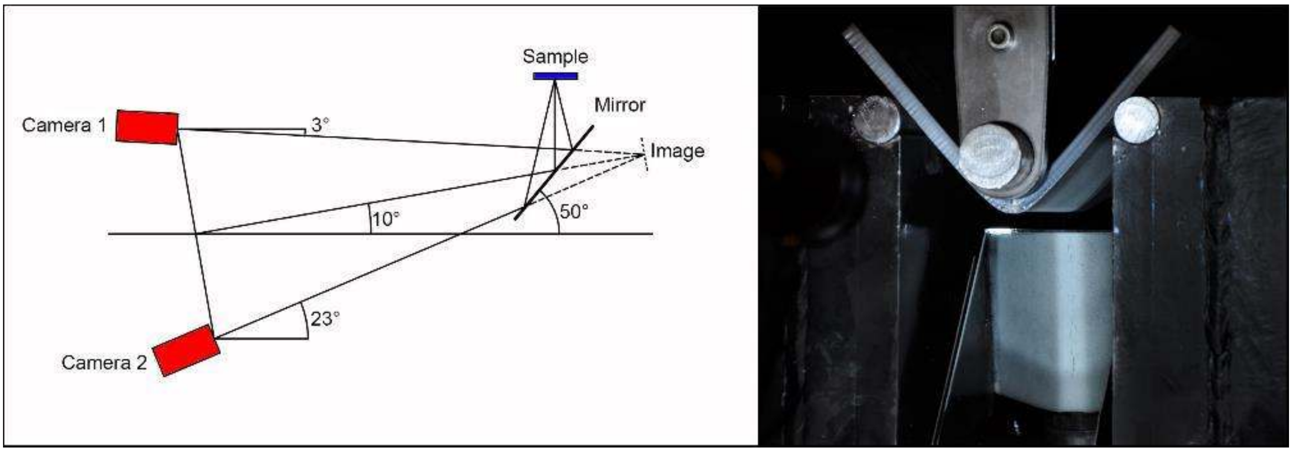

Figure 6. Positioning of cameras and mirror for ARAMIS testing in bending

The centreline of the cameras was set to slope slightly downwards in order to avoid blinding of the upper camera during the bending test when the sample was moving downwards. The optimum angle was found to be 10 degrees, in which case the lower camera was sloping 23 degrees downwards and the upper camera 3 degrees upwards. The mirror was at a 50-degree angle relative to a horizontal line, in which case the image of the sample was perpendicular to the centerline; see Figure 6.

Some bending tests were carried out for 10-mm Optim 960QC samples. The bending radius varied from 20 to 32 mm (R/t: 2.0t to 3.2t) and the sample was bent to about 90 degrees. The imaging was performed using a frame rate of 1/s. After computation one form the results were shown in a video clip where the strain distribution is seen as different colours. Figure 7 illustrates some clips from the videos, where the angle varies. In Figure 7a, R/t was 3.2 (punch radius 32 mm) and in Figure 7b, R/t was 2.3 (punch radius 23 mm).

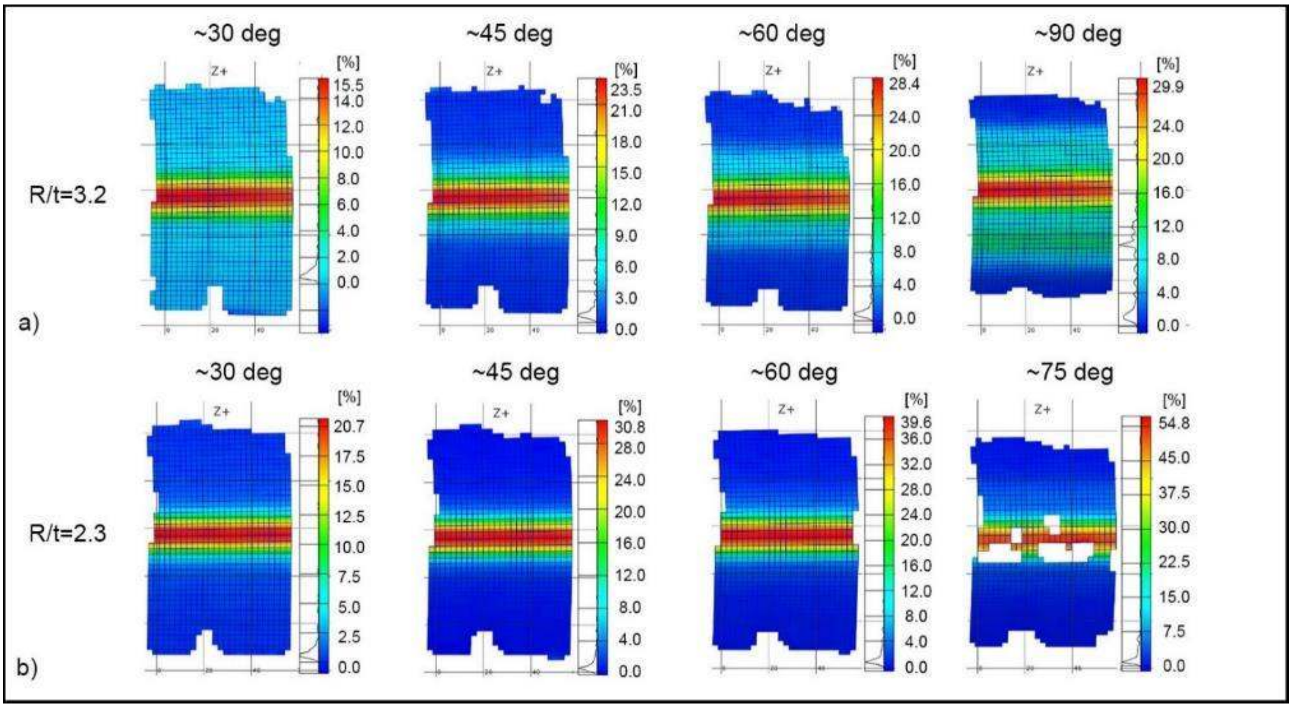

Figure 7. Strain distribution of the bend after bending with various angles and tools; a) R/t=3.2, b) R/t= 2.3. Material 10 mm Optim 960 QC

From the figures, it can be seen that with an increasing angle, the maximum strain increases as well. However, when R/t was 3.2, the maximum strain did not increase after a certain point, about 60 degrees in this case, but the strain spread over a larger area when the bending continued. When R/t was 2.3, the maximum strain increased with an increasing angle all the time and the strain was concentrated more in the middle of the bend.

In the bending test with R/t 3.2, no cracks were detected after bending through 90 degrees. With R/t 2.3, when the bending angle increased, the measurement became unstable because of the high strain. Cracking of the surface was also detected after bending, which was also seen in the cameras of the ARAMIS system. This appears in the strain distribution chart as “blind spots” or holes, which means that the strain could not be measured in these areas; see the last image in Figure 7b.

ARAMIS was also tested in direct measurement of a beam which was bent. Figure 8 shows the beam and cameras, which were positioned horizontal in this case.

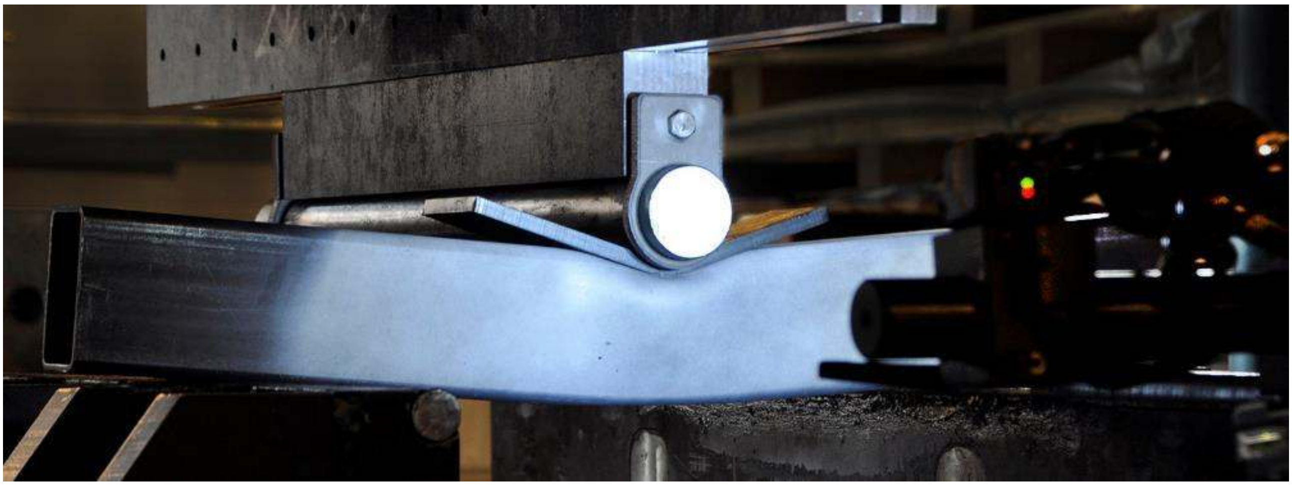

Figure 8. Optical strain analysis in bending of a beam

In this case, the surface of the beam has a two-dimensional strain condition, contrary to bending, where the strain condition was one-dimensional “plane strain”.The strain distributions on the surface of the beam in the X- and Y-directions are illustrated in Figure 9. At the bottom the beam is straining in the X-direction and in the vicinity of the punch, the surface is straining in the Y-direction because of the buckling.

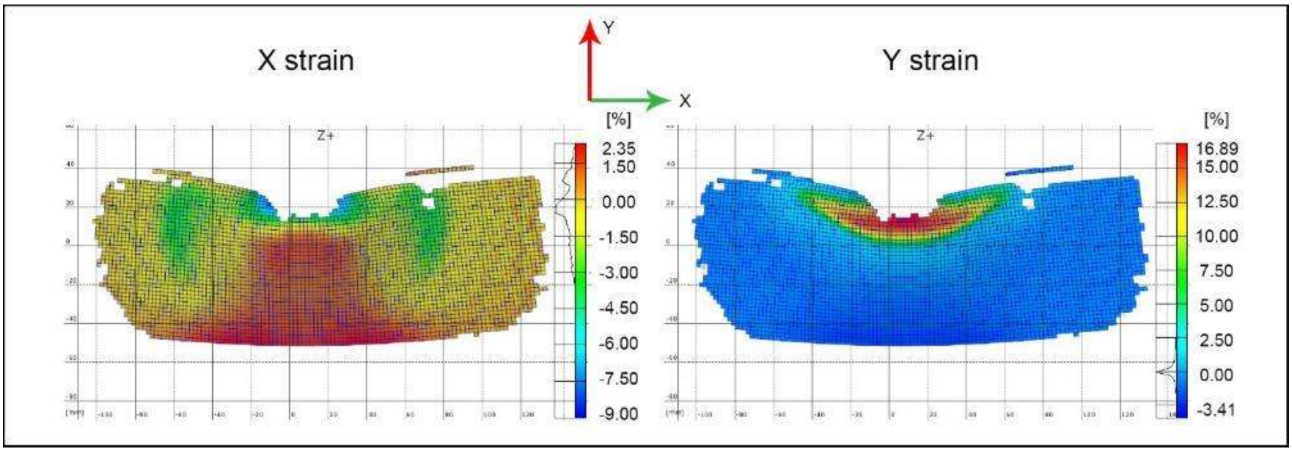

Figure 9. Strains in the X- and Y-directions on the surface of the beam

CONCLUSIONS

Three-point bending is the most common workshop process used to form steel plates. The need to bend thicker plates is increasing and it is vital to provide workshops with proper bending instructions for different steel grades. The new bending equipment at Lapland University of Applied Sciences was utilized in order to determine the bendability of thick plates. The test materials were 45mm Raex 400 and Raex 450, 50mm Strenx 700 and 80mm S355 steel grades. The quality of the bends was evaluated by visual inspection and the minimum bending radius, bending force and spring-back were determined. In addition, online temperature and strain measurements were carried out.

The results indicate that the minimum bending radii for thick plates are in good agreement with the guaranteed values for thinner gauges. It was also found that the bending force and spring-back equations can also be applied for bending of thick plates. An increase in the bending speed led to higher temperatures at the plate surface, which it is good to take into account when planning thick plate bending. The initial tests for online optical strain measurements were successful and the data gained from the tests can be used for, for example, validating bending simulations in the future.

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