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New press deflection measuring methods for the creation of substitutive models for efficient die cambering

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Abstract. Cost and time for die tryout are significant within the car industry, and elastic deflections of dies and presses are most commonly not considered during the virtual die design and forming simulation phase. Because of this, active surfaces of stamping dies are only cambered based on previous experiences of tool types and presses. However, almost all stamping dies and presses are unique, and available experiences are not valid for new materials. Partners within the Eureka SMART Advanced Manufacturing research project CAMBER have developed advanced deflection measuring devices to quantify the elastic deformations of presses. Using these measurements, cambering methodologies can be utilized in sheet metal forming simulations. Important breakthroughs in recent years enabling the cambering methodology consists of efficient simulation strategies for full scale simulations with elastic dies and optimization techniques for creating substitutive press structures based on measurements. Furthermore, modern press deflection measurement methods are beneficial in applications such as Industry 4.0, predictive maintenance, product quality control, etc. through a more advanced understanding and live monitoring of the press system.

1. Introduction

Cost and time for die tryout are significant within the car industry, and elastic deflections of dies and presses are most commonly not considered during the virtual die design and forming simulation phase. Because of this, stamping dies are only cambered based on previous experiences of tool types and presses. However, almost all stamping dies and presses are unique, and available experiences are not valid for new materials.

Important breakthroughs in recent years enabling the cambering methodology consists of efficient simulation strategies for full scale simulations with elastic dies [1-3]. The different simulation methods



have in common that they, apart from blank and elastic die, need to include numerical representations of the elastic press structure, e.g. [4-5].

Partners within the SMART Advanced Manufacturing research project CAMBER have developed deflection measuring devices based on two different sensor technologies to quantify the elastic deformations of presses.

Using the deflection measurements, numerical substitutive presses can be created. These substitutive models will be important in creating efficient FE models utilized for cambering of stamping dies.

Apart from the above mentioned advantages for die virtual spotting and cambering, the new measuring techniques enables the inline measurement of press deflections and health monitoring of the whole system. A state of the art industry 4.0 system, linked to a cloud database, is able to store historical deflection values for a given tool. The stiffness loss or press deflections increase in combination with stamping forces evolution are useful information for early detection of machine breakdowns

2. The new press deflection measuring methodology

2.1. Fiber sensors

One method to measure deflection of the press table is to use a steel beam with a glued fiber in a groove along the beam, see figure 3. This device is called a sensor beam and was used in this project in a press at Volvo Cars. Different lengths between 1030 and 2450 mm of the sensor beams have been tested as well as with and without holes through the beam for fixating the beam to the press table. The thickness of the beam is only 8 mm which reduces the distributed clamping force along the sensor beam.

Deflection of the sensor beam can be calculated with a theory based on the differential equation of the elastic curve [6], a commonly used method to describe deflection of elastic beams in solid mechanics:

$$\frac{d^2w}{dx^2} = \frac{M}{EI} \Rightarrow w(x) = \iint \frac{\epsilon(x)_{Fiber}}{z(x)} dx dx + C_1(x) + C_2$$

The equation describe the deflection of the sensor beam, and input is the strain response in the fiber along the beam and the variable $z(x)$ that describe the distance from the location of the fiber to the central of gravity for the object that deflects. The sensor beam can be mounted on the measuring object in two major ways: stuck to the surface with high clamping force and no relative movement between the sensor beam and the press table or in a way where the sensor follow the deflection of the surface but with minor shear forces and low clamping force. Advantage with a stuck sensor beam is that the strain in the fiber will be mechanically amplified. Advantage with a sliding sensor on the surface is a constant $z(x)$ and $z(x)$ is only dependent on the cross section of the sensor beam.

The strain in each beam is measured by an optical fiber with 15 Fiber Bragg gratings (FBG) distributed over the length of the beam. An FBG is an inscribed periodic modulation of the refractive index of the fiber that will reflect light with the vacuum Bragg wavelength $\lambda = 2n_{eff} \Lambda$. Here n_{eff} is the effective index of the fiber and Λ is the period of the inscribed modulation. Under longitudinal strain ϵ , the wavelength of the reflected light will shift with $\Delta\lambda = \lambda_0 \epsilon GF$ where the gauge factor GF is around 0.78.

By varying the written period of each sensor, different wavelength will be reflected and thus each sensor will reflect at different wavelengths, allowing simultaneous readout of multiple sensors in one fiber. To read out the wavelengths of the FBGs, an interrogator is used, this is an instrument with a light source and detector that allows a fast scan of many wavelengths with high wavelength precision in a short time.

The project partner Proximion process allows fully automated manufacturing of fibers with up to 30 m length and 2000 FBGs. Proximion has also demonstrated continuous distributed strain sensors [7]. For these beams, the FBGs were designed to be used with an interrogator with a scanning range of 1530 to 1570 nm.

The sensor fiber is manufactured by inscribing a 3 mm Bragg grating using 244 nm UV-light into the optical fiber at each sensor position. The FBG is stabilized in high temperature and then mounted in the groove of the beam using a proprietary gluing process.

2.2. Conventional strain sensors

The measuring technology described in subsection 2.1 was used for new validation tests at Fagor Arrasate's press-shop using a 16000kN try-out press. The aim of these tests was to analyze if a simpler measuring methodology, mounting conventional strain measuring sensors in the measuring beams, was a suitable methodology to accurately discretize the behavior of the press table.

For that, five Kistler 9232A piezoelectric strain sensors were clamped in three beams as shown in figure 1. The press was loaded using four hydraulic cylinders up to 13000 kN and at the same time two measurements were captured. From one side, the beam strains were recorded and from the other, the real press table deflection was captured using 17 linear displacement sensors (LVDTs) attached to three long profiles. This last methodology is a validated standard measuring technique used by press builders, in this case Fagor Arrasate, for the validation of the press stiffness before the shipping of the equipment to TIER1s or OEMs (see figure 2 for more information).

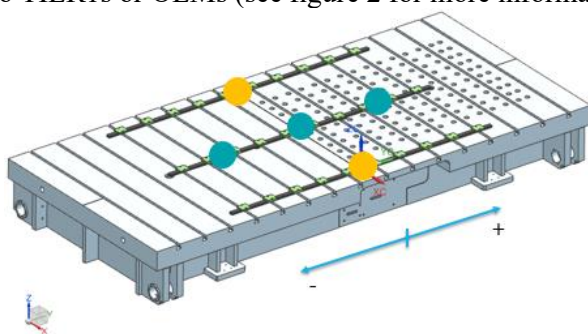


Figure 1. Set-Up of bars and piezoelectric sensors.



Figure 2. Press set-up with cylinders and gauges.

3. Experimental results

3.1. Validation of fiber sensors

Experimental tests have been made to estimate the accuracy and the effect of different mounting methods of the sensor beam on a measuring object, see figure 3, 4 and 5. The response of the measuring system is direct proportional to the deflection of the object that the sensor beam is mounted on with different mounting techniques. As expected, best method is fully fixed sensor or fully floating sensor on the object that are been measured. If there is a sliding motion due to low clamping force or low shear forces between sensor and the surface of the measured object it still is possible to measure with direct proportionality but wear in the contact can change the friction condition over time. If there is a sliding motion the friction value will determine the strain level of the sensor beam. The sensitivity of the used measuring system was higher than 0.02 mm deflection with a sensor beam floating on the surface of the bended object. If the sensor is fixed to the object the sensitivity is much higher due to mechanical amplification of the measured strain in the fiber see figure 5.

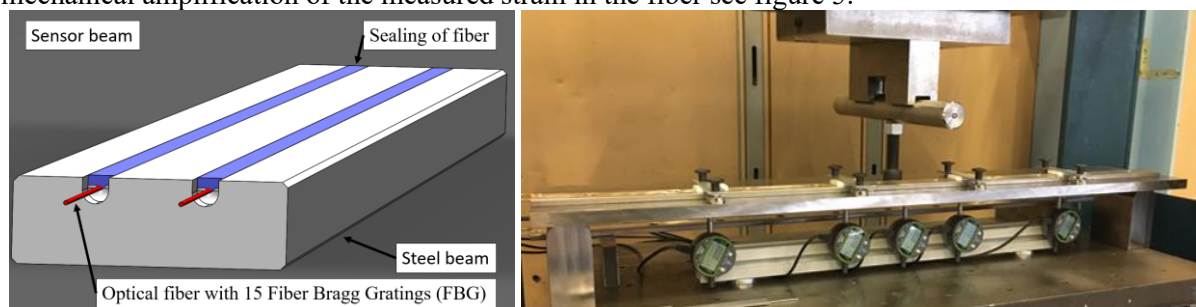


Figure 3. (Left) Sensor beam. (Right) Test of the sensor beam, sensor beam is clamped to a steel plate. Reference measuring of the deformation of the sensor beam is made with micrometre gauges.

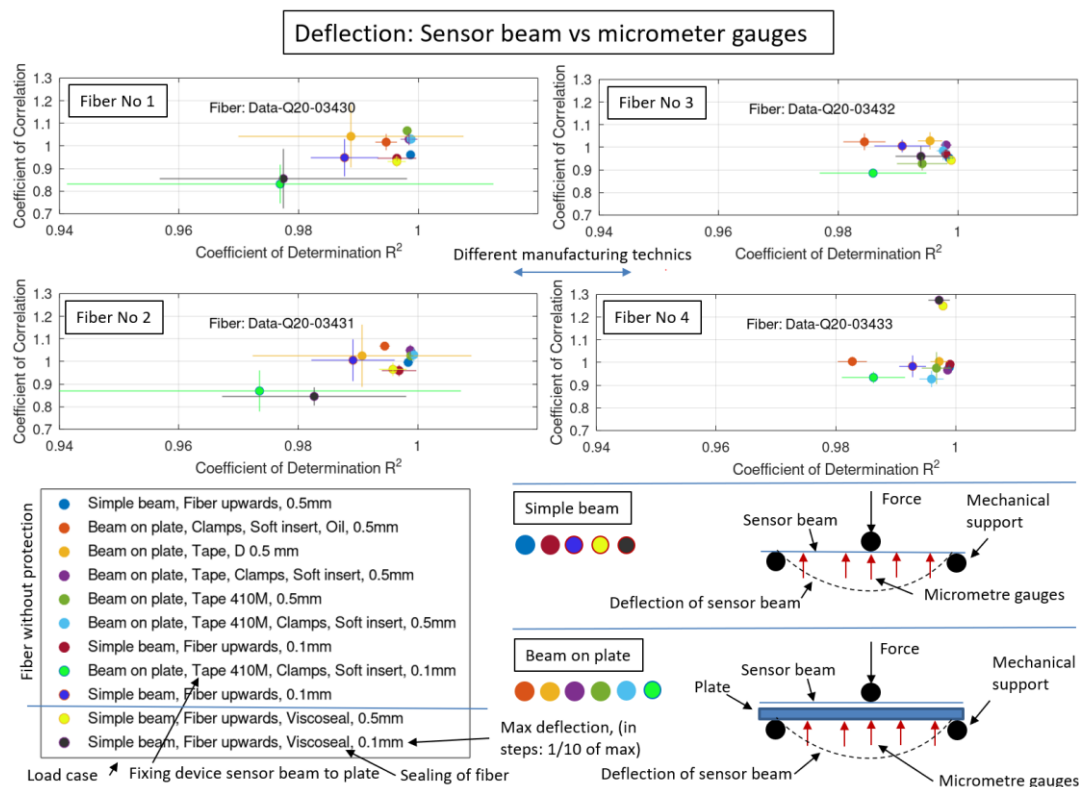


Figure 4. Examples of different clamping methods. Used test equipment see figure 3 right.

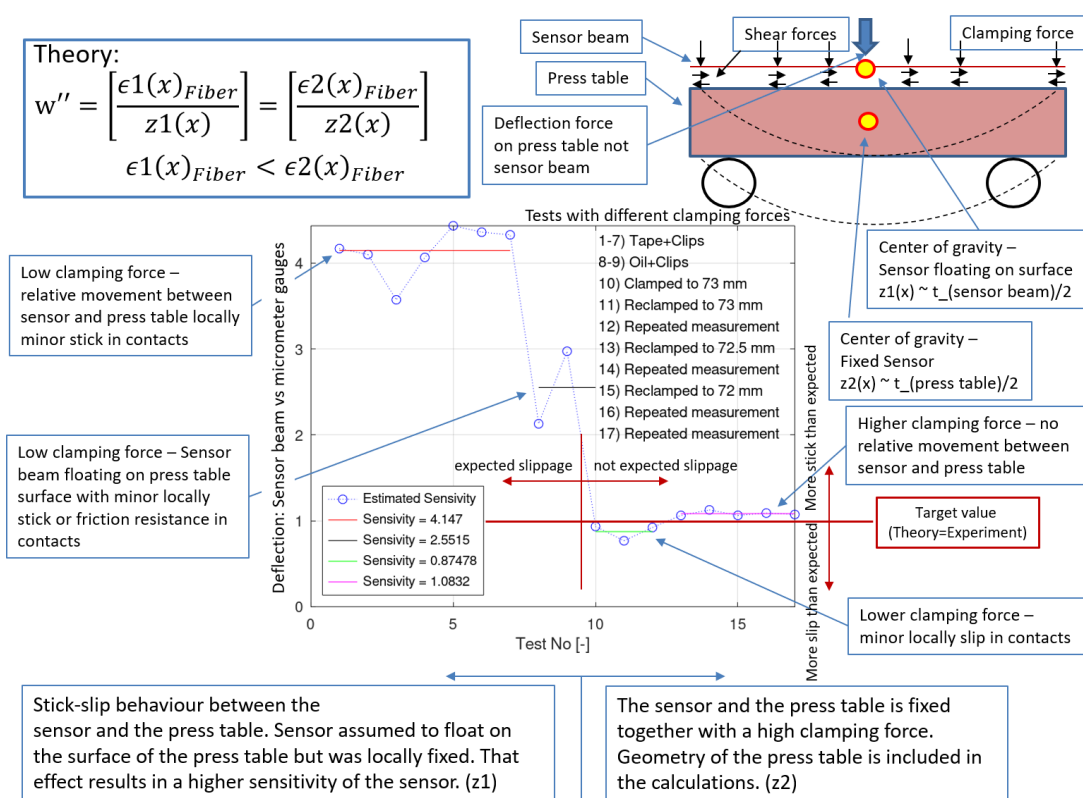


Figure 5. Sensor beam mounted on a press table with different methods and clamp force.

3.2. Validation at Volvo Cars

It is possible to measure the deflection of the press table with high precision. With the sensor beams fixed to the table, the response is amplified and give good results. The response of the fiber sensors is linear for different loads applied. Maximum load was 45% of press capacity. The measured deflection of the fiber sensor system was compared to a DIC-system (Aramis) with good correlation. This DIC-system is in previous projects compared to measuring with dial indicators, also with good correlation [2, 8]. The resolution in the displacement direction for the ARAMIS 6M system and the actual Filed of View is 1,0 mm/pixel. Subpixel calculation of the gray value image recognition make it possible to detect displacement changes below 1/10 of the actual resolution in this case better then 0,1 mm. Rigid Body Motion Compensation is used during the analyze giving that only local displacements in the analyzed part in the system is present.

Depending on the design of the table the clamping strategy needs to be adapted to the unique prerequisites. In the specific case at Volvo Cars the sensor beam was placed on the table with the mounted fibers facing upwards. On top of the sensor beam Polyurethane (PUR, Shore 90A) was placed in order to distribute the local clamping load and on top of that a hollow rectangular beam. Several steel plates with two holes were placed on top of the rectangular beam and two screws in each plate fastened the steel plate and the entire package (sensor beam/polyurethan/rectangular beam) to the table.

Deflections of the press table were provoked by loading four pillars that were placed on the table, see figure 6. The obtained result showed double curved deflections of the the table and for a specific sensor a linear behaviour was shown at all tested loads (see figure 6). The results was verified by measuring the deflection with an Aramis 3D Camera 6M from GOM. The resolution of the cameras is 2752 x 2200 pixels, maximum frame rate at full resolution is 25 frames/s and the maximum measuring volume is 2500 x 2150 x 2150 mm (w x h x d). Thereby a quarter of the table was measured in a single shot. A regression analysis of Aramis and the sensor beams was $R^2=0.91$ at 160 ton, and $R^2=0.96$ at 300 tonnes which is significant at >99.9% level and >99.9% respectively.

Deformation of press table - (160 to 500 metric tonnes)

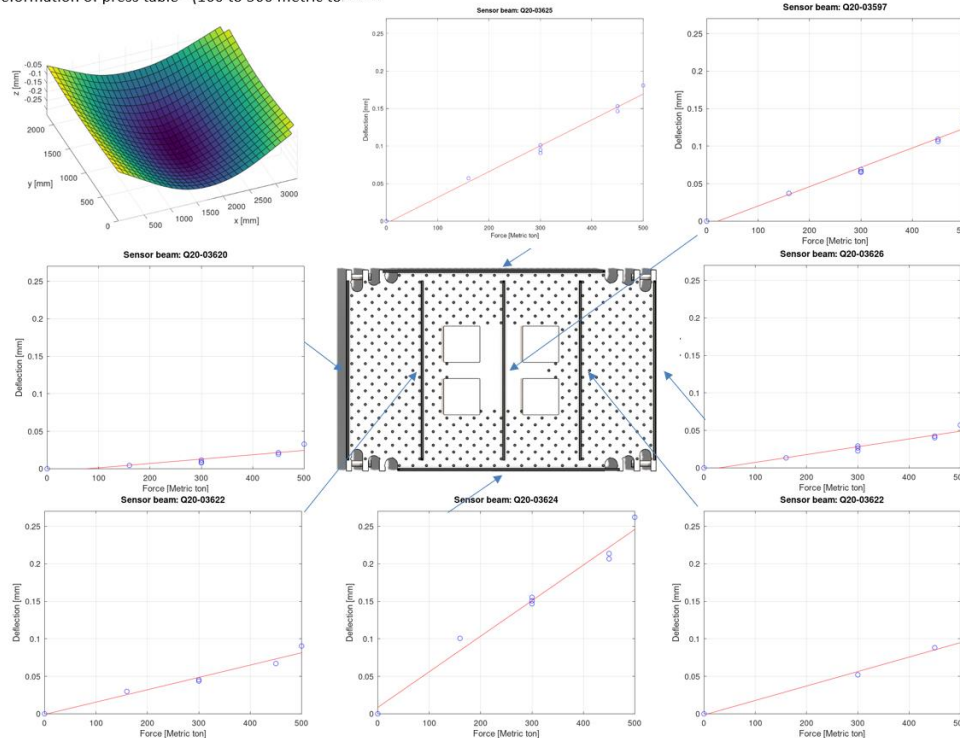


Figure 6. Deflection of the press table measured with 7 sensor beams. In all positions the deflection is direct proportional to the load. The 3D surface shows the total deflection from all sensor beams.

3.3. Validation at Fagor Arrasate try-out press

Similarly to Volvo press tests, the beams were clamped to the press table using screws and special nuts having two threaded holes that were introduced in the press table T-Slots. The upper clamping system was optimized by FEM and their shape avoids the local deformation of the measuring beams at T-Slots. The system was not floating in the press table and measurements using strain gauges in both sides of the beams demonstrated that no-slip conditions occurred during the tests between the beams and the press table. This is only possible if the clamping force is correctly distributed and high enough static friction is available in the contact surfaces.

Because the available information is quite limited in comparison to the fibers, where more measuring points are available to rebuild the press geometry, in this simplified version of the measuring system a new analytical method was used to obtain the press table geometry based on the same bending principle. Knowing the strains at sensor locations and assuming the displacement of the table at the four corners is the same (only relative movement is important for cambering) a second order polynomial was fitted for the back and front measurements and a fourth order one for the centre beam. Having the three sections the full geometry was interpolated using second order interpolation technique along the width direction. The results of the experimental tests and measured values are shown in figures 7 and 8. Note that the experimental measurements of the 17 gauges in the central beam (solid black line) presents a curved shape with two valleys. The deepest points of valleys coincide with the hydraulic cylinder locations in the press table. This table behaviour and central shape is typically observed when the presented test is performed and has been validated when simulating the experimental set-up using finite element models. This local deflections or valleys are not generated when continuous big size tools are used in the real presses and the pressure is distributed evenly. For these reasons, a fourth order polynomial seems to be good enough for the representation of the table deflection in real production situations.

The global shape of the table is well captured by the simplified measurement system and non symmetrical deflection is visible in the experimental results. This asymmetrical behaviour occurred in the real case because the selected press only has a cushion system in one side of the press (see the wholes of the pins only in one side of the press in figure 1).

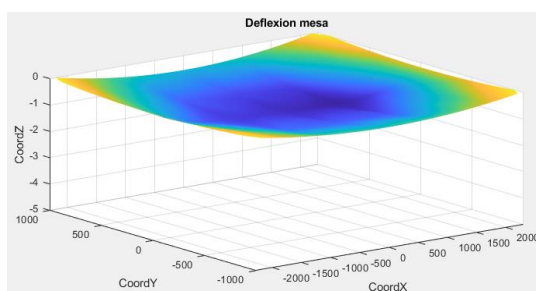


Figure 7. Spatial representation of measurements.

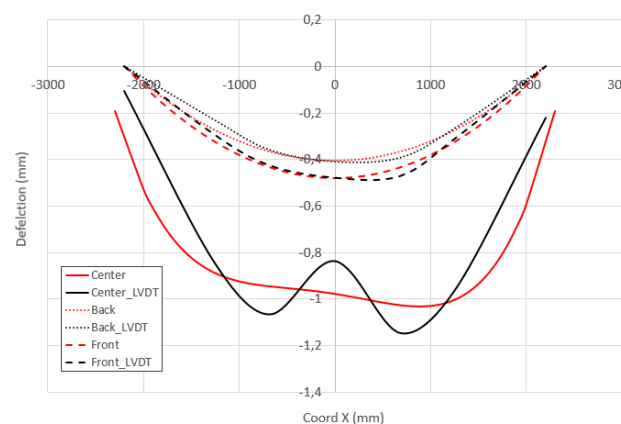


Figure 8. Beams measurements versus LVDT transducers.

4. Discussion and Conclusion

4.1. Measurements with the new beam systems

The final objective of this research work and the Camber European project was to develop deflection measuring devices, press substitutive models and finally, numerical cambering strategies based on the previous two achievements.

The deflection measuring method is based on fiber optic sensors, i.e. Fiber Bragg Gratings. The sensor beam concept was verified in the test bench. The results did show a correlation of at least $R^2=0.91$ which is significant at $>99.9\%$ level. However, the clamping strategy has a strong influence and as expected, the best method is fully fixed sensor or fully floating sensor on the object that are measured. The new innovative method was utilized to measure deflections of a press at Volvo Cars. The results were validated with an Aramis 3D Camera and digital indicator clocks (systems that are suitable for one off measurements of presses).

The simplified method using three longitudinal beams and conventional piezoelectric strain sensors was also tested using a try-out press at Fagor Arrasate. The shape calculation method is based in the bending theory, as in the case of fiber optic sensors, but the press shape is obtained using polynomial curves because the available strain measurements are not enough for a correct numerical integration. The results showed good agreement with experimental measurements although local deflections are not captured by the system. Most surely this is not important for big dimension tools and presses as the forming forces are distributed by the tools and are not localized as in the case where four pillars are used to create the deflection force.

The technology potential is not only the portability of the created devices, but even more the fact that the beams are embeddable in the press structure. This can create a try-out presses having an in-line press deflection measurement system. Firstly, the deflection measurements could be compared with the numerical deflection results in the try-out process and be useful in the trimming process.

Secondly, health monitoring and elastic behavior of try-out and production presses could be monitored over time using the created measuring methodology, using state of the art industry 4.0 systems where forming forces, tool number, oil temperature, etc. are being stored during the production of components.

In a future ideal scenario, the majority of presses could have embedded deflection measuring beams and the measurements could be compared with numerical results obtained from digital twins. Being this the case, tools could be cambered and adapted to more than one press line. This would increase the production flexibility and reduce bottlenecks in production. This will decrease unexpected breakdowns, increase the possibility for customization and shorten the lead time for those vehicles and manufacturing operations could manage fluctuating load between production units.

4.2. Substitutive models

To take press deformations into account in FE modelling of sheet metal forming processes the influence from the press needs to be modelled somehow. One way to go about this is to use substitutive models that focuses on modelling the major influencing contributions in a simplified manor as compared to using full models of the press.

Press measurements can be accounted in a substitutive model by an optimization of the model with respect to e.g. the measured deflections that gives a response in the substitutive model which in a global sense resembles the physical press behavior in a FE simulation. It is then also possible to use process simulations with substitutive models to camber the forming tools to account for occurring deformations during forming in a certain press.

Substitutive models should consist of ram, table and bolster. An example is visualized in figure 9, the method for creating the model is being developed within the CAMBER research project. The model is made of shell elements arranged as a framework underneath the ram and table surfaces that also are represented by shell elements. The table and ram can bend to deform globally according to measurements once the dimensions have been determined by optimization. Both the ram and the bolster can tilt around the two horizontal coordinate axes. The amount of tilt is determined by a non-linear resisting moment as function of the rotation angle.

Optimization of the substitutive model is done with the software LS-Opt using the measured deflection in the ram and bolster as responses in a D-Optimal sampling for a quadratic polynomial meta-model. The optimization objective is the minimization of the mean squared error of deflections with

respect to the responses. An example of results from optimization based on press measurements can be seen in figure 10 where the table with underlying framework is shown.

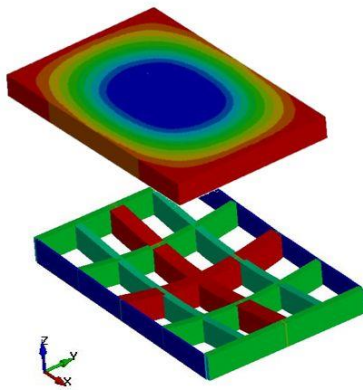


Figure 9. Exploded view of bolster with various thicknesses for the supporting framework. Deformations are exaggerated. Colour scale indicates the deformations in z-direction.

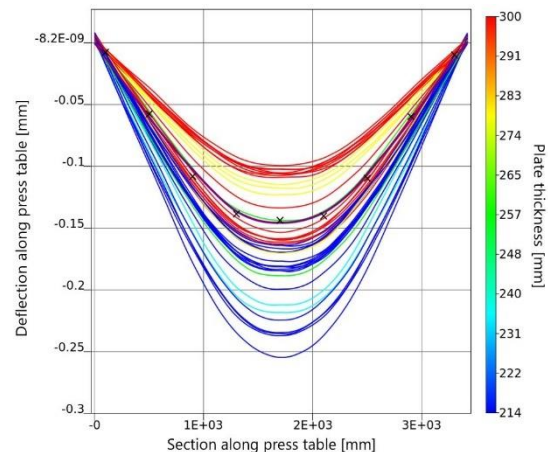


Figure 10. Output from one iteration of the optimisation of table stiffness. Curves represent different thickness configurations of the framework. Cross symbols indicate response function from actual discretized press displacement measurements.

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