Computer Aided Simulation as valid tool for sheet hydroforming process development

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ABSTRACT: Sheet Hydroforming is considered a good opportunity when it is necessary to deal with complex shapes. However, it is common knowledge that it is quite difficult to control such a kind of technology because of an appropriate press tooling is necessary and the press tooling supplier is often the technology supplier for the given problem [1]. Within a larger research program it is demonstrated that it is possible to use traditional hydraulic press tooling having the chance to manage a high level of process variables thanks to the development of a dedicated forming tool named hydroforming cell. The architecture and the number and type of process variables are developed thanks to the extensive usage of CAE techniques. An implicit solver is used to verify the structural behaviour of the hydroforming cell in terms of maximum stress levels and components stiffness while an explicit solver has helped to define the samples shapes and their main features and thanks to them it is possible to explore the process design space. An appropriate experimental phase has demonstrated the effectiveness of the developed procedure.

Key words: Sheet Forming, Hydroforming Tooling, CAE, Forming Process Control.

1 INTRODUCTION

The industrial state of the art for sheet metal hydroforming implies the usage of specific presses and specific tools. The hydroforming presses suppliers usually develop the tools design and construction; it is a matter of fact that presses suppliers are also hydroforming technology suppliers. This aspect is considered in a negative way by the technology end users who do not have the complete process control. A research program whose aim is to understand the influence and the management of the process variables on the process itself is in its development phase. One of the focal points of this project is the experimental phase during which it is essential to understand the reliability of the defined numerical models and of their output data. For these reasons, it is necessary to develop an experimental toolkit able to accomplish the research program requirements in order to test the process procedures on different shape components (as quickly and cheaply as possible). Taking into account the above described constraints, an efficient experimental equipment is developed. Computer Aided techniques have had a strategic role in order to optimize the equipment design. For the implemented solution it is sufficient the usage of a traditional hydraulic press. Two different approaches are combined to define the experimental set up:

- To improve the process knowledge four different shapes are investigated thanks to the usage of an explicit code well recognized for metal forming applications (LS_DYNA®)
- To optimize structurally the tooling performance once the process parameters is known, an implicit code (OptiStruct®) is used to evaluate stress distributions and tools stiffness in the given working conditions.

Therefore CAE tools is used as process design tools for sheet metal hydroforming. In particular, for each given shape different working conditions are investigated considering some practical constraints e.g. the maximum geometric clearance given by the chosen hydraulic press on which the hydroforming cell is installed. The maximum force exerted by the press is another key factor and for this reason it is considered as a main constraint for the process design. As a consequence of the explicit analysis campaign strategic factors like pre-forming height, punch stroke, fluid pressure characteristic and blankholder force distribution are defined for the given shapes. In the explicit analysis the tooling is considered made by rigid bodies as it is common practice for metal forming simulation. This assumption does not take into account the possible tooling deformation which has a great influence on the process performances. For this reason authors have dedicated a specific analysis phase where an implicit solver is used to define the best design for the hydroforming tools structure. In particular, in this work authors are focused on one of the studied shapes which is characterized by a geometric profile quite common for industrial applications. Different pre-forming and drawing heights is tested both numerically and experimentally. The developed numerical and experimental campaigns have increased the confidence in the process control. Appropriate process design rules is validated thanks to the experimental tests.

2 NUMERICAL SIMULATION

2.1 Test case

The philosophy of the project is to investigate the relationships between material and geometrical characteristics of the product and the process parameters. This investigation can be developed only through the use of numerical and experimental campaigns to define process performance indicators and to analyze new strategies for sheet hydroforming process tryout. To improve the knowledge in sheet hydroforming, four different geometrical shapes are investigated (Fig. 1).

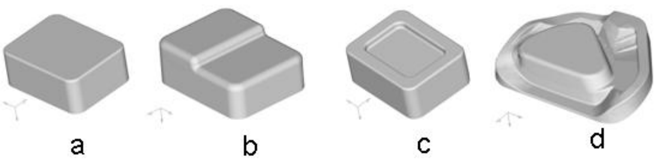

Fig. 1. Different analyzed shapes: (a) Mod1; (b) Mod2; (c) Mod5; (d) Industrial case (Fondello Fanale, FF)

For the given four models a numerical investigation is developed in order to evaluate the influence of some geometric and process parameters on the process performance. In the present work the set up conditions of one of the analyzed models defined as MOD5 is explored. The main factors of this model are described in Table 1.

Table 1. MOD5 Factors

n° Factors	Factors	Levels	
		Lower Level (LL)	Upper Level (UL)
1	Hpreforming [mm]	**15**	45
2	Thickness [mm]	**0.7**	1
3	A1 [ton]	**10**	18
4	A2 [ton]	**8**	20
5	A3 [ton]	**12**	18
6	Himb [mm]	100	**150**
7	H2 (H reverse drawing) [mm]	**20**	30
8	L [mm]	**65**	130
9	Rp [mm]	10	**25**
10	Rm [mm]	**10**	20

The Ai values are the blankholder forces applied by each actuator. In the developed hydroforming cell a total number of twelve independent actuators are available (Fig. 2). Depending on the studied shape not all these can be considered independent. In the case of the studied model named MOD5, because of the double symmetry of the models, the independent actuators are only three .

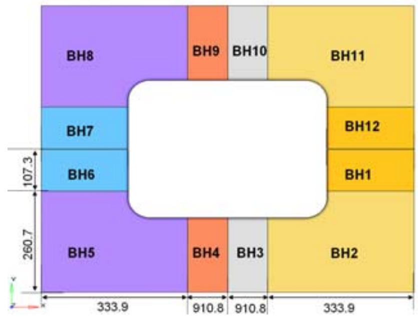

Fig. 2. Top view of the blankholder subdivision

$H_{preforming}$ is the value of the preforming height, Himb is the maximum drawing depth, R_p and R_m are punch and die radius, respectively. H_2, R_1, and L (Fig. 3) are added to the geometric parameter in order to fully define the geometric profile of the formed part.

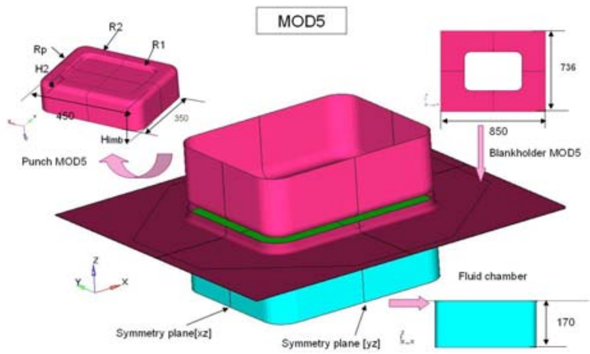

Fig. 3. Factors of MOD5

Analyzing MOD5, it is possible to investigate how much deep a reverse drawing could be without having ruptures.

Finite element analysis (FEA) is used to understand the deformation behaviour of a material during the hydroforming process (Fig. 4). Only a quarter of the model is considered for symmetry reasons. The commercial finite element code LS-Dyna® [2] is used to run the simulations. HyperMesh® is used to create the finite element mesh, to assign the boundary conditions and to build LS-Dyna® input deck for the analysis.

One of the most important factors to be considered when performing a numerical analysis is to use a constitutive model that accurately captures the behaviour of the material. A power law constitutive model ($\sigma = K\varepsilon^n$) is used to represent the material behaviour for a low carbon steel (FeP04). The factors values used for the explicit simulation described in this paper are highlighted by bold font in Table 1.

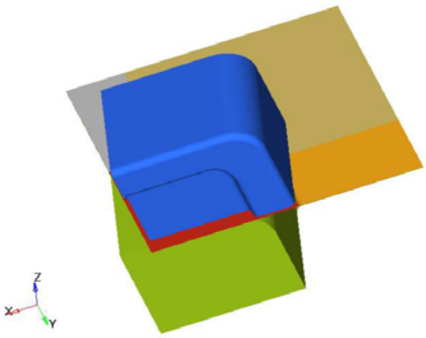

Fig. 4. FE Model created for the sheet hydroforming process simulation

2.2 *Implicit Numerical Simulation*

Numerical simulations of metal forming processes traditionally consider tooling as rigid bodies components. This assumption has great effect in terms of run time reduction thanks to the fact that tooling components are not computed as deformable bodies by the used explicit code. At the same time, the adoption of this solution presents some limits in comparison with the real simulated set up. In fact, following this procedure it is not possible to evaluate which the influence of the tools stiffness is on the process performances. This aspect becomes particularly relevant in the case of the blankholder structure. Blankholder has a strategic role in metal forming processes because, thanks to its action, it is possible to manage the sheet flow in as a control parameter for possible ruptures and/or wrinkles [3]. Within a larger activity oriented to establish effective connections between process performances and its variables for sheet metal hydroforming, authors [4] have developed a numerical procedure which aims to increase the numerical simulation reliability. Each die component is verified in terms of stress and strains distribution under working conditions generated by the hydroforming process. A 3D linear static finite element analysis is carried out, using the linear FE code Optistruct®. As reference, Fig. 5 illustrates the general procedure used to analyse the pressure distribution transferred by the actuators to the blankholder active surface.

Fig. 5 also shows the obtained displacement and Von Mises stress distributions for upper blankholder in the case of the MOD5 model. The FE model of the analyzed structures is modelled using tetra solid elements (CTETRA4) with the relative boundary conditions to simulate the real behaviour of the structure. This analysis is useful to evaluate the stiffness of each tooling component.

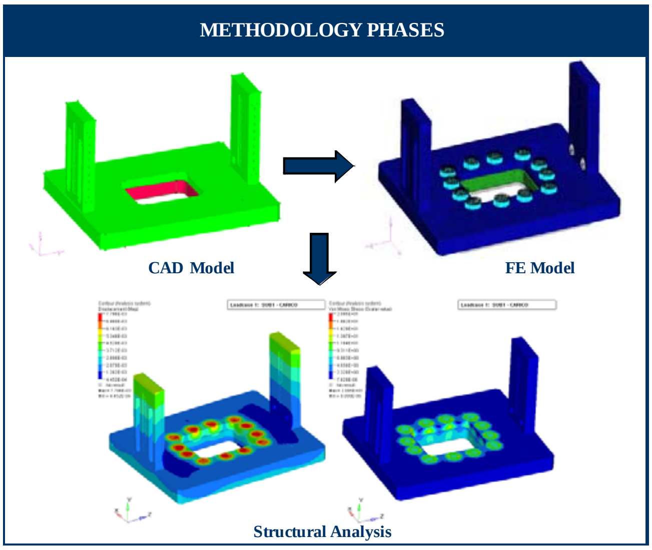

Fig. 5. Phases of adopted Methodology

This activity allowed for understanding the way to transfer the clamping force of each actuator through the structural component on the active surface of the blankholder. Pressure maps are obtained on the clamping active surface as output of this activity. As reported in Fig. 5, it is possible to assert that the actuators load transferred from the upper part to the active surface of the tool depends on the tool geometry itself [5].

3 EXPERIMENTAL TOOLING

In order to avoid ruptures and wrinkles, the hydroforming cell is designed in the way to manage a differential blankholder force around blank rim and during the hydroforming process. A configuration with twelve hydraulic actuators is chosen to obtain the time – space variable blankholder force profile. The actuators size and shape avoid interference between themselves. Their position around the blankholder edge is defined in order to minimize the distance from the fluid chamber (Fig. 6).

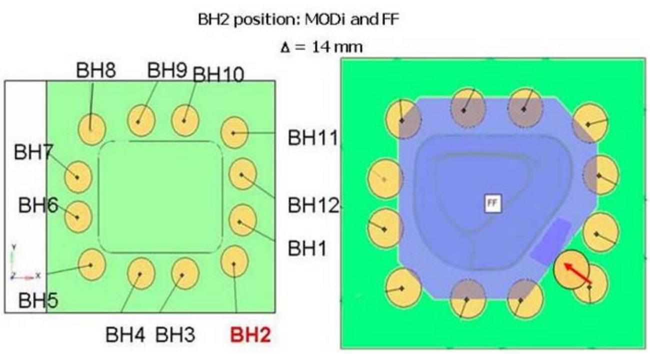

Fig. 6. Setup of the actuator

Hydroforming cell is made up of a lower part (with a lower blankholder positioned onto the fluid chamber and together over a base plate, a static seal is positioned between the fluid chamber and the lower blank – holder, a dynamic one is in the same lower blank – holder in an apposite machined seat) and an upper part (with the twelve actuators and their hydraulic and electric equipments mounted inside an upper base mounted on the upper press table). The forming tool is made by a punch (a in Fig. 7A) mounted onto the punch – holder (c) base integral with the upper base. The actuators (b) and the fluid chamber are provided with two hydraulic valves (the proportional and the maximum ones) to manage fluid pressure during the working cycle. Conical log or cilindric shaped dowel distribute or concentrate respectively the applied load of each actuator (e). Another fundamental device to set proper pressure in each actuator is the magnetostrictive measure line because, load path for actuators and fluid chamber is punch displacement dependent (e in Fig. 7B). The cell is a modular device to reduce costs and time when it is necessary to test different shapes. CAE analysis allowed for a definition of parameters and steps of the process utilized to design the cell and its control software in accordance with technological constraints of the chosen hydraulic press.

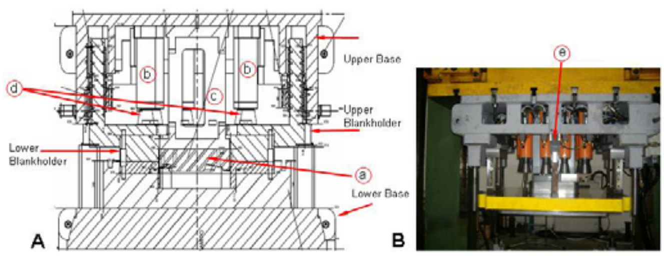

Fig. 7. Cell structure and cell onto press

The tooling control software is a LabView® application running on a PC and hosted by the National Instruments **cRIO** controller hardware (compact **R**econfigurable **I\O**), mounted in an appropriate case and communicating with the industrial PLC of the press (Siemens S100 with software Step5) (Fig. 8). Cycle activation is made through the control panel of the press. The user can control the sequence of the process through an appropriate interface (**GUI**, **G**rafic **U**ser **I**nterface) of the control software of the cell (Fig. 9).

The identified hydroforming process phases are:

1. Metal sheet placement on the fluid chamber (executed by an operator);
2. Fluid chamber filling;
3. Spilling of actuators;
4. Upper part of cell translation until pre-forming position;
5. Pre-forming;
6. Deep drawing;
7. Coining with pressure increment to a specific value for a certain time;
8. Decompression of the fluid chamber and then of the actuators;
9. Upper cell uplift.

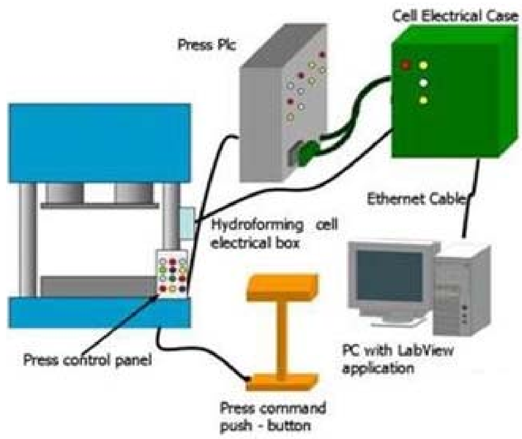

Fig. 8. Scheme of Communication

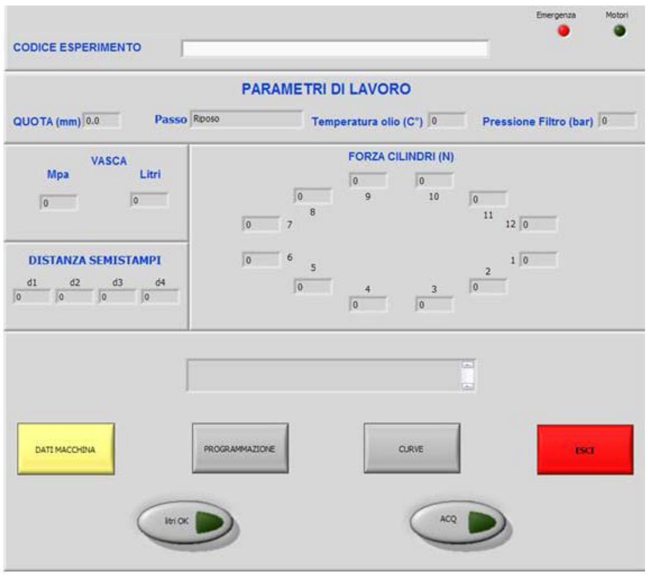

Fig. 9. Software Control Panel (GUI)

A dedicated software routine manages every single phase. Pre – forming height is obtained through the inlet of the fluid volume needed to reach it. This parameter is a CAE output. A fluximeter controls the injected volume and this parameter is visualized on the cell GUI. For each proportional valve a pressure transducer acquires the effective pressure in order to compare input data with the experimental ones allowing for the verification of the numerical–experimental correlation. An automatic procedure allows for the drawing of the data from three files containing numerical input and experimental data. It also analyzes the obtained data comparing graphs in terms of pressure – punch displacement curves for the fluid chamber and force – punch displacement for each actuator. The numerical – experimental correlation allows for the:

- Understanding of the cell behaviour with consequent modifications (if necessary) of tooling geometry and of its control system;

• The usage of acquired data as input to improve simulation models.

The comparison between a real workpiece and a virtual one, obtained with a FE analysis, is a fundamental phase of the research activity to verify simulation models reliability and finally to validate the entire simulation procedure (Fig. 10).

The described procedure is applied to the MOD5 test case in the following configuration:

Material: **FeP04** (low carbon steel); blank Thickness: **0.7 [mm]**; Actuators Force: **LLL** (which means the lowest possible value); H_{imb} (drawing height): **150 [mm]**; R_p (Punch radius): **25 [mm]**; R_m (Die Radius): **10 [mm]**; H_{pref} (Preforming height): **15 [mm]**; H_2: **20 [mm]**; L: **65 [mm]**.

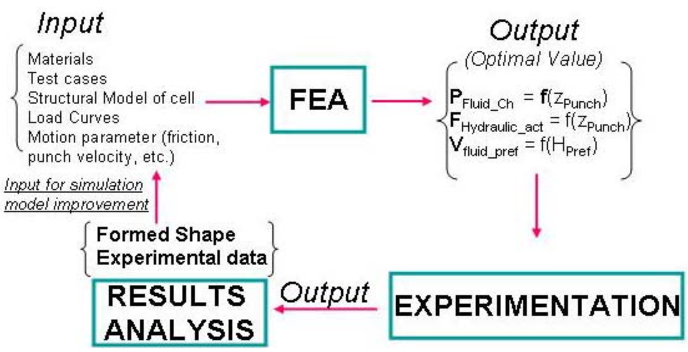

Fig. 10. The numerical – experimental correlation phase

4 NUMERICAL –EXPERIMENTAL CORRELATION

Fig. 11 reports the FE model and the effective plastic strain distribution of the hydroformed blank at the end of the punch stroke. Large deformations can be seen at the peripheral region near the vertical fillet of the walls and it is also evident a local portion of the flange affected by little wrinkles.

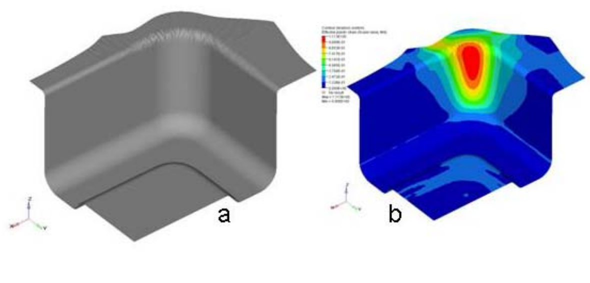

Fig. 11. (a) Fe Model; (b) Effective Plastic strain at the end of the die stroke

As shown in Fig. 12, a uniform thickness distribution in the part is achieved after hydroforming except in the zones affected by wrinkles.

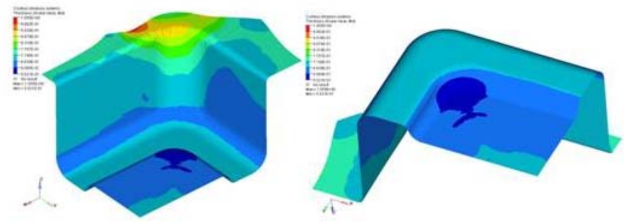

Fig. 12. Thickness distribution

In order to understand the effective deformation state of the part it is also necessary to analyze the major and minor strains distribution on an appropriate Forming Limit Diagrams (FLD) (Fig. 13) where the feasibility of the model without ruptures is evident.

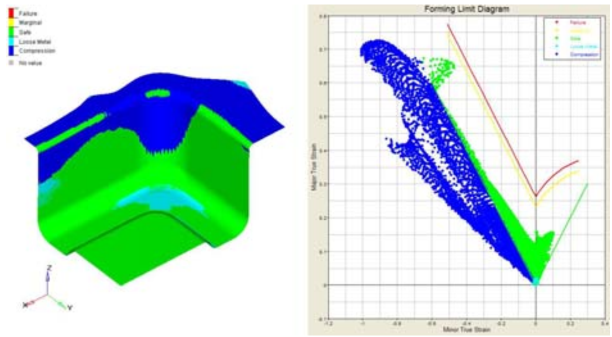

Fig. 13. Major and minor strain distribution

Comparing the FE model final shape (Fig. 11) with the real ones (Fig. 18) it is evident a good match between the numerical analysis and the real hydroforming process for the model. It can be observed a good agreement of the wrinkles area in the flange zone. The following graphs show and compare the input load path for the fluid chamber and actuators 1, 2, 3 with data acquired by pressure valves transducers.

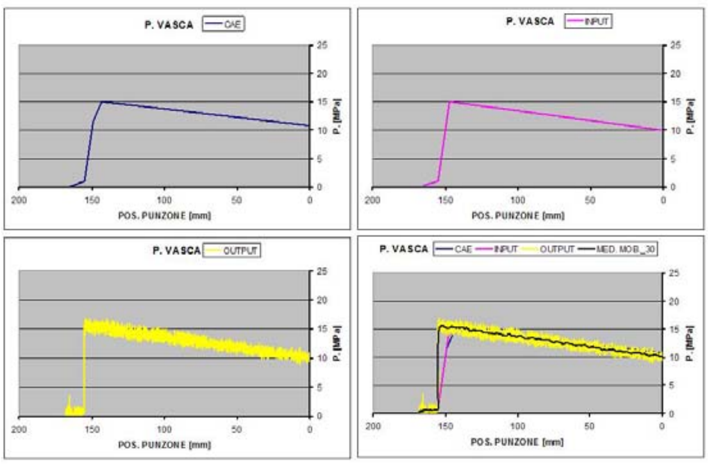

Fig. 14. Pressure in fluid chamber

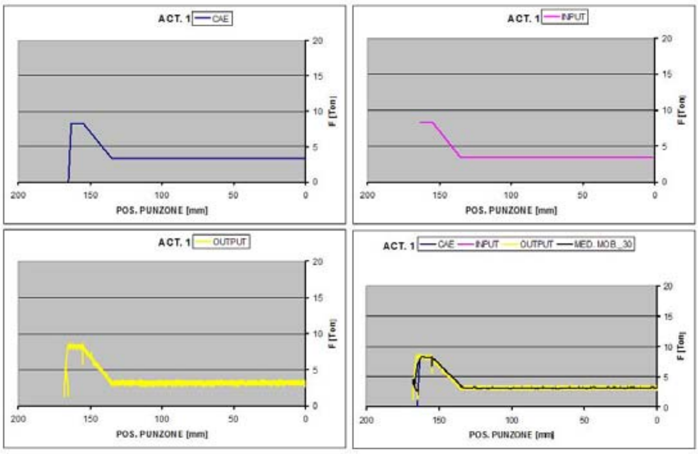

Fig. 15. Actuator 1 load path

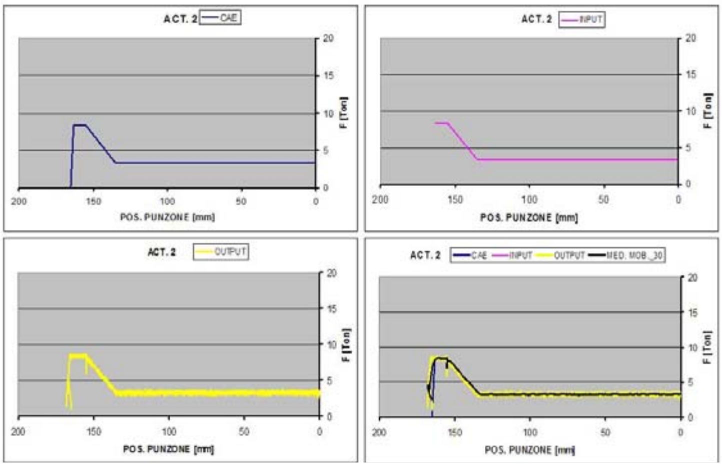

Fig. 16. Actuator 2 load path

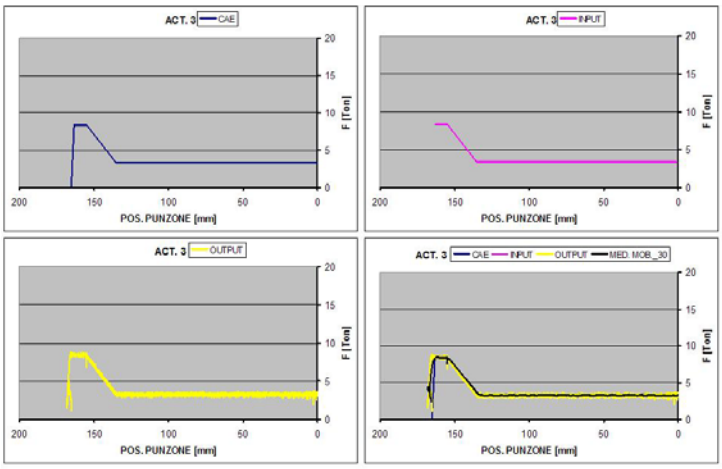

Fig. 17. Actuator 3 load path

Fig. 18. Real Model

The good correlation between input and acquired data is demonstrated.

5 CONCLUSIONS

The illustrated usage of CAE tools usage has demonstrated its effectiveness as valid support for the investigation of a non conventional forming technology like sheet metal hydroforming is. The experimental campaign will continue in the next future in order to combine the obtained qualitative results with quantitative indications which can be acquired thanks to local measures of thickness reductions measured in specific regions of the formed specimens. Moreover, the defined procedure will be investigated for different materials classes e.g. the aluminum alloys.

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