DESIGN OF A PROTOTYPE OF SERVO HYDRAULIC MULTIAXIAL **TESTING MACHINE FOR SPECIMENS, STRUCTURAL ELEMENTS** AND STRUCTURES

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ABSTRACT

This report concerns the design of a machine devoted to test on specimens, structural elements and frames in multi-axial conditions of load, displacement and deformation. The machine was considered as a system constituted in synthesis, of load frame, power supply, oil-hydraulic actuators, and electronic devices for control, monitoring and testing procedures.

The different phases of the work start from analysis of functional characteristics to construction and assembling of mechanics, actuating and control groups.

More precisely the load frame, that is the subject of the present work, was designed on the basis of functional criteria, stiffness, constructive aspects, modularity, assembling facilities of elements and test specimens.

Keywords: Axiomatic Design, Stiffness Criteria, Modular elements.

1 INTRODUCTION

In the field of test equipments we distinguish, on the basis of the functions, mainly some types of machines: standard monoaxial and biaxial machines; especially designed equipments to test well defined industrial products (furniture doors, chairs, washers and so on), universal machines for different types of tests.

The first ones are focused on the characterization of materials in static and fatigue conditions under uniaxial and biaxial loads or displacements.

The latter types must have a great versatility in order to offer different configurations to operate, also with the aid of mechanical interface equipments, applying loads in different direction.

For example in [1,2] a machine to test large size aeronautic panels in bi-dimensional traction-compression and shear is presented and the characteristics and performance in static and fatigue conditions are listed. In [3] the authors described an interesting biaxial machine for in plane honeycomb crushing tests.

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Since the frame was built for a testing machine, the guidelines of the design were essentially oriented by the need for an accurate displacement and compliance control.

Structural aspects and frame behaviour were simulated by FEM analysis for different load positions to the aim of optimizing bolted and welded joints. Therefore some joining configurations of oil-hydraulic actuators on the structure were analyzed utilizing numerical procedures and considering principally displacements and compliances as the responses to be optimised whilst the actuators positions where regarded as parameters.

2 DESCRIPTION OF THE TEST MACHINE

The main aspect that is surely to be pointed out refers to the versatility provided by a complex design and that allows tests on specimen, elements or frames of complex geometry under static and variable loads applied in any direction in the 3-D space.

In particular the machine is a servo-hydraulic system whose properties are synthetically listed below.

Actuators:

n. 4 actuators with hydrostatic bearing;

- static capability: \pm 20 kN;
- dynamic capability: \pm 10 kN;
- stroke: 100 mm;

- maximum load frequency: 100 Hz with displacement \pm 0.1 mm

Electronic control device:

The control is performed by a modular multi-station and multichannel unit that allows independent management of each actuator with the capability of feedback compensation.

Load frame:

The frame consists in a platform (size 4.5x4.5 m²) with tee slots in two direction and a three dimensional structure (height 3 m, width 4 m) having four/three arches equipped with slots for positioning and fixing actuators. Further modular structural members constitute auxiliary supports for actuators or specimens.

In this paper we refer to two different constructive solutions of the machine the first one named Four Legs (4L) (Figure 1) and the second one named Three Legs (3L) (Figure 2).

As aforesaid, the platform has reverse tee slots that permits to fix structural and auxiliary members and actuators. In more details the main structure consist in arches, bolted on supports applied to the platform.



Figure 1 – Four Legs Multi-axial Test Machine



Figure 2 – Three Legs Multi-axial Test Machine

Each circular arch is formed of modular curved elements that consists in two C welded profile connected each other as in Figure 2, with a gap in order to consent the mounting, in any angular position, of the actuator connections.

The actuators are connected to the frame by means of modular link elements (Figure 3) which consent to constraint the actuators in any position along the slot that is located between the two coupled components of the arches. They consists in three elements: two thick plates with ledges and a rod threaded at the extremity. The plates have the important function to distribute the load on an extended contact surface avoiding localized effects and have also different shape in order to fit internal or external surface of frame.



Figure 3 – Link elements for actuators

The external mounted plate has a central hole, the internal has lugs or threaded holes to constrain respectively as a hinge or as a

fixed support the hydraulic actuator. The lugs avoid the effect of torsion or warping that can arise in the two C elements of the frame as shown in Figure 4.



Figure 4 – Position 30 deg – a) Displacement uz – b) torsion effect on C profiles

3 FEM DISCRETIZATION DETAILS

In order to analyze different constructive configurations and load conditions, a mesh was realized such as to reduce the computational time without significant loss of accuracy on the results. With reference to the frame, eight node shell elements were mainly used obtaining meshes with about 47000 elements for 4L (Figure 5) and 36000 elements for 3L (Figure 6) configuration respectively.



Figure 5 – Four Legs mesh



Figure 6 – Three Legs mesh

Due to the very high stiffness of the basis platform, that is also fixed on the ground, the frame constraints, realized by using bolted joint, were modelled as directly clamped to the ground. The unilateral effect due to the variable bolt contact areas introduces non linearity in the solution. The effect was separately considered by individuating effective areas of reaction in presence of traction, compression and tilting forces (Figure 7).

Finally, in order to analyze the static behaviour of the structure and check the sheet sizing and the position of the ribs and links, two different kinds of load condition were adopted. The first one, named "relative", consists of balanced loads within the structure; the second one, named "absolute", consists of externally applied loads balanced by ground constraints.

4 BOUNDARY CONDITIONS

4.1 CONSTRAINTS

The legs are constrained by bolted joints inserted in the platform slots. Such a link, even if pre-loaded, is an unilateral constraint and its modelling introduces non linearity in the finite element solution. Furthermore the effect of the bolt is distributed in a limited area around the hole of the bearing plate that is welded to the leg.

For this reasons we analyzed separately the problem of bolt preload, related to possible gaps, and the distribution of the reactions individuating active areas in different load conditions. In this way we had useful data for assembling the frame and, since several load cases were required, for reducing the computational effort by avoiding time consuming convergence problems. In the analysis of various cases by applying traction and tilting forces, we assumed some simplified configuration of distribution of constrained nodes (Figure 7).

In Figure 7 a schematic representation of contact areas between the bearing plates and the platform is shown. In this zones the constraints related to the specific load case were applied.



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Figure 7 – Constraint zone for traction and tilting forces

4.2 LOAD CONDITIONS

In order to avoid singularity problems due to concentrated forces, the effect of load distribution, provided by the plates of the linking system of the actuators, was simulated by a pressure distribution on the elements in the contact area. This aspect is essential in order to take into account the displacements just in that zone and determine the direct and cross stiffness that are strongly needed in order to correctly sizing the mechanical members.

In order to simulate some possible test arrangements, a lot of load cases were analysed by considering different types of load, according to the aforesaid criteria. In particular, different angular positions of absolute force were examined.



Figure 8 – Load conditions for four and three legs configuration: a) relative loading in the plane x,z - b) relative loading in the plane x,y - c) absolute loading in the plane x,y

In Figure 8 are depicted the described load conditions both for four legs and three legs frames.

5 RESULTS

In the design of test machine it is of great interest the static and dynamic displacement response. In fact stresses and strains are very small and do not have relevant interest, except sometimes in some singular zones, for designing purpose.

The present design was mainly aimed at providing a strong machine stiffness and, for this reason, the results are studied with reference to displacements and presented in terms of compliance responses, for all the examined load cases.

5.1 FOUR LEGS



Figure 9 – Displacements of 4L frame under relative load. Position 0 deg a) Displacement ux = uz; b) Displacement uy

The contour plot of deformed shape of 4L frame is shown in Figure 9. The displacement ux = uz, due to the symmetry of the model, and the displacement uy were obtained by considering four internally balanced forces, applied to a plane parallel to the x,z plane as shown in Figure 8 a).

Point A	Cx [µm/kN]	Cy [µm/kN]	Cz [µm/kN]
	0,02	0,58	0,00
Loading	$Cr [\mu m/kN]$	$C\theta$ [µrad/kN]	Cz [µm/kN]
point	-0,76	-0,05	0,00

Tab. 1 – Compliance in the point A and on the loading area for relative load case in the plane xz

Tab. 1 lists the compliances in x, y and z directions in A, see Figure 8, that was assumed as a reference point for comparison of results. In the same table direct compliances in polar coordinates, evaluated in correspondence of load points, are presented.

Φ [deg]	Cx [µm/kN]	Cy [µm/kN]	Cz [µm/kN]
0	3,32	0,63	-0,03
15	4,80	0,79	-0,04
30	5,53	0,78	0,03
45	5,10	0,41	0,01
60	4,15	-0,48	-0,05
75	2,16	-0,98	0,15
90	0,03	-1,25	-0,06

Tab. 2 – Compliance of point A in μm/kN versus load angular position (maximum values)

The list of compliances relative to different load angular positions is reported in Tab. 2. The compliances were evaluated by considering the maximum value of displacements in the cross zone of the frame (A). The same values are plotted in Figure 10.



Figure 10 – Compliance of point A in µm/kN versus load angular position (maximum values)

In Tab. 3 and Figure 11 the compliances are shown, referred to the loading points, for different angles.

The evaluation was performed by considering average displacements of loaded areas.

Φ [deg]	Cr [µm/kN]	$C\theta [\mu rad/kN]$	Cz [µm/kN]
0	-3.55	-0.64	0.00
15	-6.00	-1.83	0.00
30	-6.22	-2.88	0.00
45	-6.55	-3.33	0.00
60	-4.62	-3.26	0.00
75	-2.98	-1.76	0.00
90	-1.19	0.00	0.00





Figure 11 – Direct and cross compliance in loading points, expressed in μm/kN and in μrad/kN versus load angular position (average values)

<figure>

Figure 12 – Displacements of 3L frame under relative load. Position 0 deg a) Displacement ux; b) Displacement uy; c) Displacement uz

The contour plot of deformed shape of 3L frame is shown in Figure 12. Due to the asymmetry of the model with respect to the plane x,y the displacements up were obtained by considering two internally balanced forces applied to a plane parallel to the x,y plane as shown in Figure 8 b).

Point A	$Cx [\mu m/kN]$	$Cy [\mu m/kN]$	$Cz [\mu m/kN]$
Loading	0,03 Cr [µm/kN]	0,99 Cθ [µrad/kN]	0,89 Cz [µm/kN]
point	-1,20	-0,13	-0,01

Tab. 4 – Compliance in the point A and on the loading area for relative load case in the plane xz

Tab.4 lists the compliance in x, y and z directions in point A, see Figure 8, that was assumed as a reference point for comparison of results. In the same table direct compliances in polar coordinates are presented, evaluated in correspondence of load points.

Φ [deg]	Cx [µm/kN]	Cy [µm/kN]	Cz [µm/kN]
0	3,35	0,80	0,84
15	5,04	1,38	1,39
30	5,81	1,31	1,32
45	5,39	0,61	0,64
60	4,45	-0,68	-0,71
75	2,46	-1,60	-1,78
90	0,07	-2,30	-2,04

Tab. 5 – Compliance of point A in μm/kN versus load angular position (maximum values)

The list of compliances relative to different load angular positions is reported in Tab. 5. As said before, the compliances were evaluated by considering the maximum value of displacement in the cross zone of the frame. The same values are depicted in Figure 10.



Figure 13 – Compliance of point A in µm/kN versus load angular position (maximum values)

In Tab. 6 and Figure 14 the compliances are shown, referred to the loading points, for different angles.

Also in this case the evaluation was performed by considering average displacements on loaded area.

Φ [deg]	Cr [µm/kN]	$C\theta [\mu rad/kN]$	Cz [µm/kN]
0	-3,68	-0,32	-0,02
15	-6,92	-1,96	-0,17
30	-6,81	-3,09	-0,34
45	-6,55	-3,47	-0,59
60	-4,73	-3,25	-1,07
75	-3,86	-1,69	-1,72
90	-2,06	0,00	-2,02





Figure 14 – Direct and cross compliance in loading points, expressed in μm/kN and in μrad/kN versus load angular position (average values)

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6 DISCUSSION OF RESULTS

In the previous sections, with reference to the analysis of static behaviour of a test machine frame, some relevant results, obtained using methodology based on a FEM code [4,5], are reported.

By considering the compliances of reference point A in the case of relative loading, the symmetry of 4L frame is verified. Referring to the results obtained for 3L configuration in the same case, a small compliance in z direction, due to asymmetry of the structure, can be observed.

The direct compliances, which were obtained loading 4L and 3L frame respectively with four and two opposite loads, show, obviously, a better behaviour for the first configuration.

In the cases of absolute loads, the influence of angular load position on cross compliance in point A and on direct compliance in the load point, presents greater value, relatively to the component Cx and Cr in correspondence of angular positions of about 15-45 deg. respectively. The small values of cross compliances demonstrate the reduced attitude of the structure to undergo relevant displacements in directions different from the loading direction. The maximum compliance value in any case is below the limits commonly assumed for test machines.

7 CONCLUSIONS

In this paper, it has been presented an approach to design a structure that is to be constructed in a single prototype. Criteria of modularity and versatility in the choices of shape of structural elements were adopted. Due to the specific functions of the machine, that is to test mechanical elements, the design was oriented by the assumption that the structure stiffness is an essential requisite.

8 REFERENCES

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