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National Aerospace Laboratory NLR

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RESIN TRANSFER MOULDING AS FABRICATION METHOD FOR COMPLEX SHAPED COMPOSITE COMPONENTS FOR SPACE APPLICATIONS

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ABSTRACT

Composites are being used increasingly for structural components for aircraft and space applications. Up to now, the autoclave process is the standard fabrication technique to produce these components. Recent developments show the evolution of new fabrication techniques and of composite materials for these fabrication techniques. One of these new fabrication techniques is Resin Transfer Moulding (RTM). The RTM fabrication concept is based on the injection of resin into a mould cavity containing dry fibres (preform). During the injection process, air in the mould is being replaced by resin and the fibres are impregnated.

The RTM fabrication concept has several advantages compared to autoclave processing:

A two sides tooling concept can be used, assuring tight outer dimensional tolerances, hence reducing the amount of shimming during assembly. Net-shaped or nearly net-shaped components can be made, hence reducing the amount of trimming after curing of the composite component. Complex shaped components can be made.

In order to investigate the feasibility of RTM for the fabrication of complex shaped composite components with concentrated load introductions, several technology programs are being carried out at NLR. The present paper will present the results of two technology programs: a bracket for a launcher and a torque link for a landing gear.

THE COMPOSITE BRACKET

The first case presents the development of a composite bracket for a launcher rocket

THE METAL REFERENCE BRACKET

Figure 1 presents the aluminium bracket that was used as a reference in this study, which is incorporated in the Ariane IV launcher. This metal bracket is made out of aluminium and has a weight of 314 gram. Figure 2 presents the load cases for which the metal bracket was designed.

MATERIALS USED FOR THE COMPOSITE BRACKET

The composite bracket was composed of the following materials:

- SA Injectex GF420-E01-100 2.5 D (420 gram/m^2) carbon fabric with HTA fibres. This fabric is a multi-layer balanced fabric, which means that an equal amount of fibres is present in both the warp and weft direction. The mechanical properties of such a fabric are not as good as for a unidirectional fabric. However, this fabric has excellent drapability characteristics and was therefore used in the double curved areas of the bracket.
- SA Injectex GU230-E01-100 unidirectional (230 gram/m^2) carbon fabric with HTA fibres. This fabric has 90% of its fibres in warp and 10% of its fibres in weft direction. Because of the unidirectional nature of the fabric, this fabric has excellent mechanical properties. However, the drape performance of this fabric is very poor. Therefore this fabric was used in the single curved highly loaded areas of the bracket.
- Epoxy resin LY5052 and hardener HY5052 to impregnate the fibres. This is a resin with a reasonably low viscosity for a long period and has a curing temperature of 80 ^{0}C.

The material properties of the materials used (needed as input for the finite element calculations) were determined by testing specimens in tension (250 mm x 25 mm x 3.5 mm) and compression (45 mm x 40 mm x 3.5 mm).

DESIGN OF THE COMPOSITE BRACKET

The composite bracket was designed with the finite element code B2000 (ref. 1), which is in use at NLR as a testbed for developments in computational mechanics. Nine node anisotropic shell elements (354 elements) were used to model the composite bracket. It was decided to keep the interface between the bracket and the backing structure the same as for the metal bracket in order to make a retrofit possible. Therefore the same kind and number of pin-loaded holes, High-locks and bolts were used in the composite bracket as in the metal reference bracket (see fig. 2). However, the general layout of the composite bracket was allowed to be different from that of the metal reference bracket. The pin-loaded holes were modelled by introducing the load in two nodes, one node on each side of the bracket. The bolts and high locks which connect the bracket to the backing structure were modelled by using boundary conditions that lock all six degrees of freedom in the corresponding nodes in the base of the bracket. The Design Ultimate Load was multiplied with a factor of 1.15, because at the time the bracket was designed, it was not certain whether a fibre volume fraction of 58% (the fibre volume fraction of the specimens used to determine the material properties) could be achieved in the composite bracket.

The bracket was optimised for minimal weight with the optimisation module B2OPT (ref. 2) within B2000. This optimisation code minimises the weight of the bracket while the design is subjected to constraints on stresses. In order to carry out an optimisation of the laminate of the bracket, the following six sections with five sub-laminates were defined (see fig. 3):

Laminates before the optimisation:

Section 1: $[45,0,45]_{sublam.1}[0,90,0]_{sublam.2}[45,0,45]_{sublam.5}$.

Section 2:
$[45,0,45]_{sublam.1}[45,0,45]_{sublam.5}$.

Section 3:
$[45,0,45]_{sublam.1}[0,90,0]_{sublam.2}\ [0]_{sublam.3}\ [90]_{sublam.4}$
$[45,0,45]_{sublam.5}$.

Section 4:
$[45,0,45]_{sublam.1}[0]_{sublam.3}\ [90]_{sublam.4}[45,0,45]_{sublam.5}$.

Section 5:
$[45,0,45]_{sublam.1}[0]_{sublam.3}\ [90]_{sublam.4}[45,0,45]_{sublam.5}$.

Section 6:
$[45,0,45]_{sublam.1}[0,90,0]_{sublam.2}[45,0,45]_{sublam.5}$.

For the optimisation the following 10 design variables were defined (see fig. 3):

Design variable 1: Height H.
Design variable 2: Width W1.
Design variable 3: Width W2.
Design variable 4: Length L.
Design variable 5: Number of 45^0 plies in sub-laminates 1 and 5 of sections 1 to 6.
Design variable 6: Number of 0^0 plies in sub-laminates 1 and 5 of sections 1 to 6.
Design variable 7: Number of 0^0 plies in sub-laminate 2 of section 1, section 3 and section 6.
Design variable 8: Number of 90^0 plies in sub-laminate 2 of section 1, section 3 and section 6.
Design variable 9: Number of 0^0 plies in sub-laminate 3 of section 3, section 4 and section 5.
Design variable 10: Number of 90^0 plies in sub-laminate 4 of section 3, section 4 and section 5.

Sub-laminates 2 to 4 were composed of the unidirectional fabric GU230-E01-100, whereas sub-laminates 1 and 5 were composed of the 2.5 D fabric GF420-E01-100. As mentioned before, the composite bracket had to be a functional replacement of the metal bracket, therefore a side constraint was defined to ensure that the composite bracket stayed within the available assembly window of the metal bracket.
The minimum dimensions of the bracket near the pin-loaded holes were designed by basis design rules (see fig. 4). These values were used as side-constraints for the optimisation. These side-constraints were set to values that ensured a bearing failure mode since this failure mode has a fail-safe character (ref. 3). The Tsai-Hill stress criterion was used to predict laminate failure. The elements near the load introductions were left out in the determination of laminate failure as these elements were expected to give unrealistic high stresses as a result of the simplifications in the finite element model.
As a result of the optimisation the following sub-laminates in sections 1 to 6 were obtained:

Laminates after the optimisation:

Section 1:
$[45_2,0,45_2]_{sublam.1}[0_3,90,0,90,0_3]_{sublam.2}[45_2,0,45_2]_{sublam.5}$.

Section 2:
$[45_2,0,45_2]_{sublam.1}\ [45_2,0,45_2]_{sublam.5}$.

Section 3:
$[45_2,0,45_2]_{sublam.1}[0_3,90,0,90,0_3]_{sublam.2}[0_3,90,0,90,0_3,90,0_3]_{sublam.3\ and\ 4}\ [45_2,0,45_2]_{sublam.5}$.

Section 4:
$[45_2,0,45_2]_{sublam.1}\ [90_2,0_3,90_2,0,90_2,0_3,90_2]_{sublam.3\ and\ 4}$
$[45_2,0,45_2]_{sublam.5}$.

Section 5:
$[45_2,0,45_2]_{sublam.1}\ [90_2,0_3,90_2,0,90_2,0_3,90_2]_{sublam.\ 3\ and\ 4}$
$[45_2,0,45_2]_{sublam.5}$.

Section 6:
$[45_2,0,45_2]_{sublam.1}\ [0_3,90,0,90,0_3]_{sublam.2}[45_2,0,45_2]_{sublam.5}$.

Figure 5 shows the dimensions of the composite bracket after optimisation. After optimisation, a buckling analysis was performed to check the stability of the bracket. The first buckling mode occurred at 8.5 x Design Ultimate Load.

FABRICATION OF THE BRACKET

Figure 6 presents an exploded view of the mould that was developed to fabricate the composite bracket by RTM. All mould elements were made of aluminium with the exception of the central part that was made of the elastomer Techtron HPV. This elastomer was selected because of its large coefficient of thermal expansion, which eases demoulding of this mould element after curing of the bracket. The modular

character of the mould is apparent from fig. 6. Because of this modular concept, sub-preforms could be prepared very easily on the tapered mould elements and the Techtron central part (see fig. 6). Once these sub-preforms were made sub-laminate 5 was placed on the sub-preforms to complete the preform of the bracket. Then, the preform was positioned in the mould. The mould was closed and resin was injected through a central injection hole. Eight vents were used to evacuate the air during injection of the resin. Resin was injected with 3.5 bar and without vacuum assistance.
Based on a cost estimation it was decided not to fabricate the bracket net shaped but to machine the cured bracket to the required dimensions because cutting the sub-preforms to the net-shaped dimensions without fibre distortion at the edges would become very difficult, time consuming and therefore expensive due to the small dimensions of the bracket. Figure 7 shows a bracket after machining. A fibre volume fraction of 55% was achieved in all brackets that were produced. C-scans made of the cured brackets, indicated no entrapped air, delaminations or dry spots.
The weight of the bracket after machining was 173 gram. The weight of the aluminium bracket was 314 gram. This means that a weight reduction of 43% has been achieved.

TESTING THE COMPOSITE BRACKET AND TEST RESULTS

One of the brackets was tested in tension and compression. Six rosettes (type HBM 6/120RY11) were used to measure strains during the tests. Before the tests two steel bushes were positioned in the pin loaded holes of the bracket. The tests were carried out displacement controlled with a velocity of 0.1 mm per minute. The bracket was designed for 1.15 x (Design Ultimate Load)$_{metal\ bracket}$. Since the tests were carried out at ambient conditions an environmental knock down factor of 20% was used during the tests. This resulted in the following test program:

- 0.575 x Tension Design Ultimate Load
- 0.575 x Compression Design Ultimate Load
- 1.15 x Tension Design Ultimate Load
- 1.15 x Compression Design Ultimate Load
- 1.38 (= 1.2 x 1.15) x Tension Design Ultimate Load
- 1.38 (= 1.2 x 1.15) x Compression Design Ultimate Load.

The bracket did not fail during these tests. The measured strains corresponded well with the predicted FEM results.

THE COMPOSITE TORQUE LINK

The second case presented is the development of a composite torque link for landing gear applications. The composite torque link was developed in the framework of a landing gear technology program in collaboration with the following partners: SP Aerospace and Vehicle Systems, MARC Analyses b.v., Eurocarbon and NLR. For this component, SP Aerospace and Vehicle systems delivered the specifications and assisted during the preliminary design phase, MARC Analyses carried out finite element calculations and NLR made the preliminary design, developed the preforming and RTM tooling concept, fabricated several torque links and carried out static tests.

THE METAL REFERENCE TORQUE LINK

Figure 8 presents the metal (aluminium) torque link. The torque link is composed of two elements: an Upper Torque Link and a Lower Torque link. In landing gear applications a torque link is used to prevent the landing gear wheel from shimmying during landing operations. The weight of the metal torque link was: 182 gram for the Lower Torque Link and 175 gram for the Upper Torque Link. Design Ultimate load for the metal torque link was 4.548 kN (see fig. 8).

MATERIALS USED FOR THE COMPOSITE TORQUE LINK

The composite torque link was composed of the following materials:

- SA Injectex GF420-E01-100 2.5 D (420 gram/m^2) carbon fabric with HTA fibres.
- RTM-6 epoxy resin. RTM-6 is a one-component epoxy resin with a curing temperature of 160 ^{0}C. This resin combines excellent mechanical properties (comparable with standard epoxy resins which are used within the aerospace industry) with a low viscosity (! 50 mPa.s) at 120 ^{0}C for a reasonable period (! 90 minutes).

The material properties of the materials used (needed as input for the finite element calculations) were determined by testing specimens in tension (250 mm x 25 mm x 3.5 mm) and compression (45 mm x 40 mm x 3.5 mm) specimens.

THE COMPOSITE TORQUE LINK DESIGN

The composite torque link was designed in a way that both the Upper Torque Link as well as the Lower Torque Link can be produced in the same mould in order to limit tooling costs. During the preliminary design phase the torque link was optimised for minimal weight by the finite element code B2000 (ref. 1) and the optimisation module B2OPT (ref. 2). To make the optimisation possible the following sections were defined (see fig. 9):

Sections 1 and 4:

- Lay-up: $[45,0_2,-45,0_2,90,0_2,-45,0_2,45]$
- E_{11} : 73681 N/mm^2
- E_{22} : 22562 N/mm^2
- G_{12} : 11594 N/mm^2
- $\mp_{12}$: 0.40
- $\mp_{21}$: 0.12

Section 3:

- Lay-up: [45,0,-45,0,90,0,-45,0,45]
- E_{11} : 58833 N/mm^2
- E_{22} : 28270 N/mm^2
- G_{12} : 14777 N/mm^2
- $\mp_{12}$: 0.41
- $\mp_{21}$: 0.12

Design variables were the thickness of these different sections. After optimisation, laminates were sized for these sections. A detailed finite element analyses of the optimised torque link was made by Marc Analyses (ref. 4). The FE models were full three-dimensional models consisting of eight-noded brick elements (MARC element type 7). MARC's automatic contact algorithm (ref. 5) was used to describe the contact between the bolts and the pin-loaded holes. No friction was modelled between the bolts and the pin-loaded holes. Figure 10 presents the final Torque Link design.
The weight of the final composite Upper Torque Link is 121 gram. In comparison to the weight of the aluminium torque link (175 gram) a weight reduction of 31% has been achieved.
The weight of the final composite Lower Torque Link is 129 gram. In comparison to the weight of the aluminium torque link (182 gram) a weight reduction of 29% has been achieved.

FABRICATION OF THE COMPOSITE TORQUE LINK.

Both the Upper and Lower torque link were produced in the same mould. Figure 11 shows the exploded view of the RTM mould. The mould was composed of aluminium elements in combination with an elastomer (Techtron) core element. With this mould six torque links (both Upper and Lower) were produced simultaneously by cutting the cured component into six slices. Resin was injected through the central injection hole. During resin injection the mould was heated to 120 ^{0}C. The resin was injected without vacuum assistance. The injection pressure was 5.0 bar. Several torque links were produced and inspected by C-san. The fibre volume fraction of the torque links was 58%. Before being tested aluminium bushes were mounted in the holes needed for the load introductions.

TESTING THE COMPOSITE TORQUE LINKS

Several Torque Links were tested. The tests were carried out under displacement control with a velocity of 1.0 mm/min. Figure 12 shows the test set-up. All torque links were tested and failed beyond their Design Ultimate Load Level. Unfortunately, at the time this paper was prepared, no comparison between measured and calculated strain levels had yet been made.

CONCLUSIONS

This paper presents the results of two case studies in which complex shaped components with concentrated load introductions were fabricated by RTM. The studies demonstrated that such components can be made successfully. All components outperformed their specifications. Weight savings of 29%-42% were achieved.

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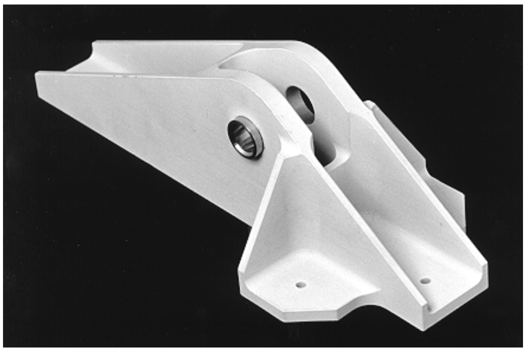


Fig. 1 Metal bracket

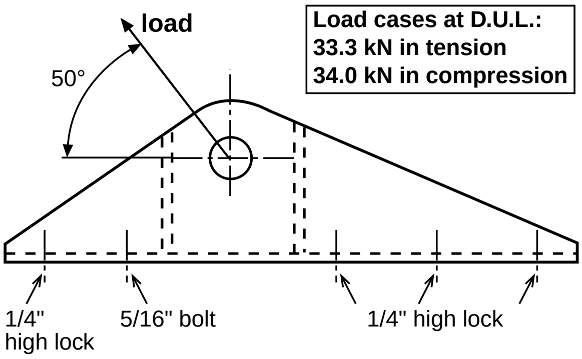


Fig. 2 Static load cases for the metal bracket

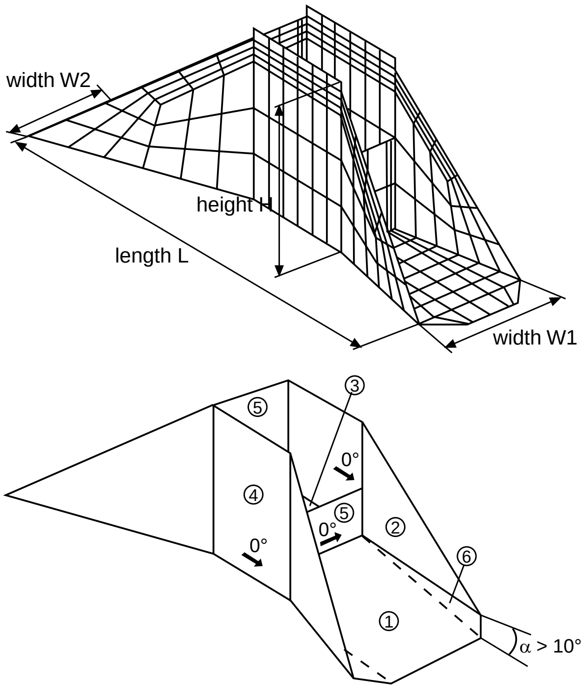
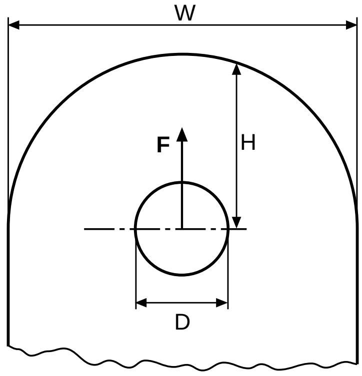


Fig. 3 Geometric design variables and sections 1 to 6



For a given hole diameter D and load F:

Thickness t determined by bearings stress: $t = F/(D \times \sigma_{bearing})$

Width W determined by tensile stress: $W = (F/(t \times \sigma_{tension})) + D$

Height H determined by shear-out stress: $H = F/(2 \times t \times \tau_{shear\text{-}out})$

Fig. 4 Global sizing of a pin-loaded hole

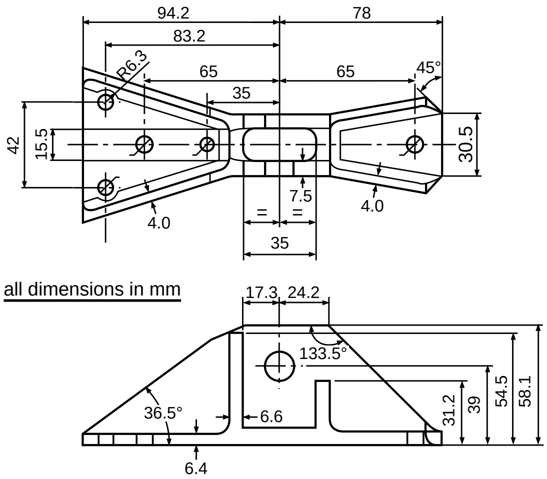


Fig. 5 Dimensions of the composite bracket after optimization

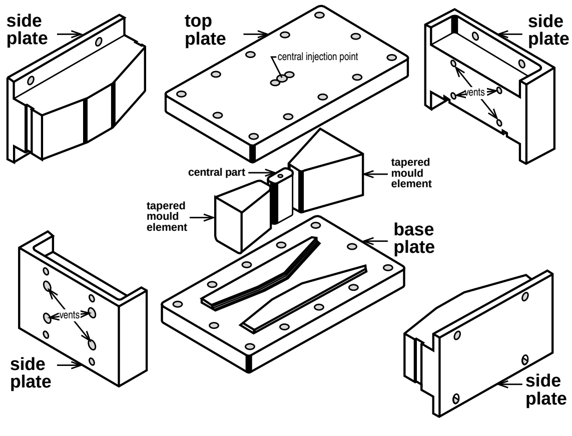


Fig. 6 Elements of the RTM mould

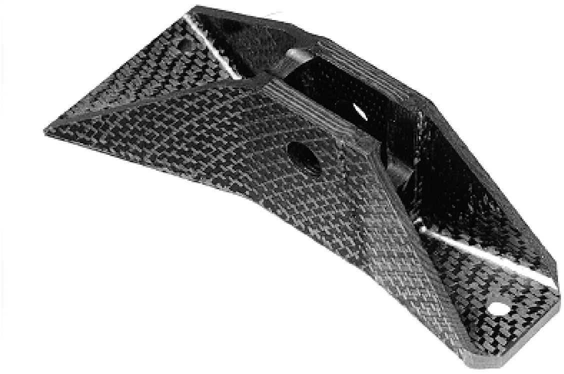


Fig.7 Composite bracket

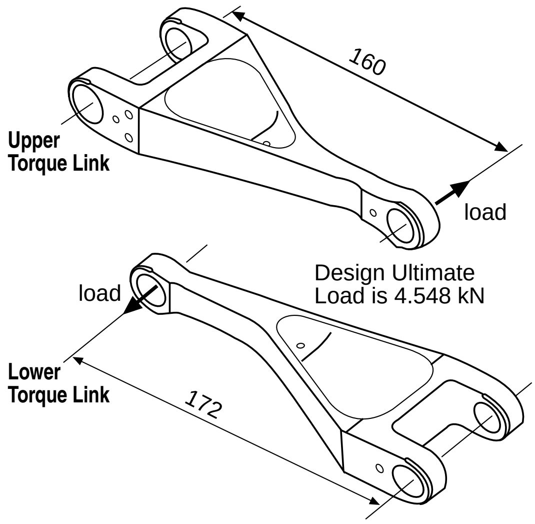


Fig. 8 Aluminium reference torque links

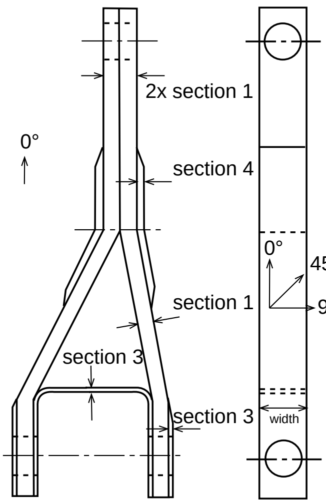


Fig. 9 Torque link during the preliminary design phase

Fig. 10 Torque link design (bold Upper and Lower Torque links)

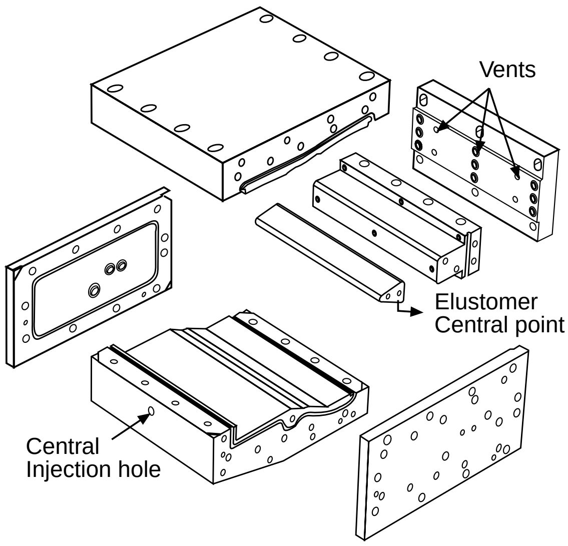


Fig. 11 Exploded view of RTM mould for the production of composite torque links

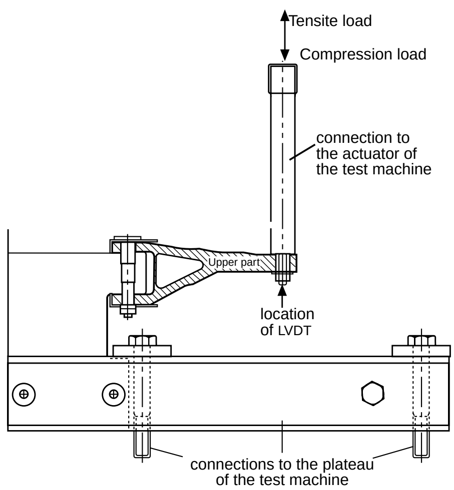


Fig. 12 Test Set-up to test Torque Links