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Report:

In this allocated beamtime, we recorded the dynamic inside the cavity of a pristine fastener assembly subject to 3.4 kA current at the microsecond time scale by using high-speed XPCI. Then, the damaged fastener is analysed by using phase contrast tomography.

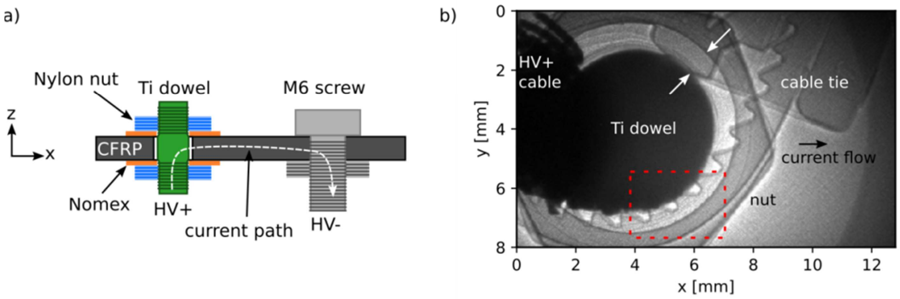

Figure 1. a) Scheme of the academic fastener assembly. b) Top view of the cavity recorded by the high-speed XPCI setup. One can see the dowel, the edge of the nuts, the high voltage cable on the left-hand side and the Nylon cable tie used to attach it. The cavity is marked by the two white arrows. The current flows from left to right. The red dashed box is the zoomed area reported in Figure 2.

The sample is composed of a CFRP panel and only two fasteners, allowing for simplified circulation paths of current in the structure (Figure 1a). The CFRP panel is 4.1 mm-thick and 20 mm x 50 mm in size. It is made of sixteen plies of aligned T700 carbon fibres (Toray, diameter of 12 ± 3 µm), surrounded by Epoxy resin M21 (Hexcel) [1]. The successive plies are oriented at -45° and +45° which guaranties that all the plies contribute equally to the transport of current between the two fasteners. The studied fastener cavity is formed by a Titanium dowel with a diameter of 5 mm and a central flat length of 4 mm inserted in a hole with a diameter of 6.5 mm. This configuration has been chosen to facilitate the imaging of the cavity from above. A particular care is taken to centre the fastener on the cavity. The dowel is tightened to the panel by two Nylon nuts. A dielectric washer made of NOMEX T410 with 185 µm thickness, adjusted to the dowel diameter, is inserted between the nut and the panel to ensure that the current flows inside the dowel and to seal the cavity. The current is injected through the dowel (HV+). It is delivered by a current generator specially designed by ONERA. The generator provides a single pulse of current with a biexponential waveform. The maximum of 3.4 kA is reached in roughly 14 µs and it decreses to half of it in roughly 40 µs. The cavity is imaged 14 m downstream on a visible high-speed camera (Hyper Vision HPV-X2 from Shimadzu) using a scintillator. The camera has a sensor made of 400 x 250 pixels, with a pixel size of 32 µm, resulting in a field of view (FOV) of

about 12 mm x 8 mm (magnification of 1). The behaviour of the cavity is recorded at a speed of 500 kHz with an exposure time of 200 ns. To achieve these recording conditions, the white beam (peaked at 30 keV) is chosen to maximize the photon flux. The camera is synchronised with the generator and starts to acquire 1 µs earlier than the current injection. The current returns through the second fastener (HV-), which is a stainless steel M6 screw mounted in interference fit to avoid arcing on this side.
The image of the cavity is shown in Figure 1b. We can see the dowel in black, highly attenuating the beam. Thanks to phase contrast, edges are emphasized: the cable tie (visible teeth around the dowel) used to fasten the HV+ cable, the Nylon nuts and the cavity seen through the nuts (marked by the two white arrows). One can notice that the dowel is not perfectly cantered on the cavity, with the shortest Ti-CFRP distance reached in the bottom-right area of the cavity. The current flows from left to right.

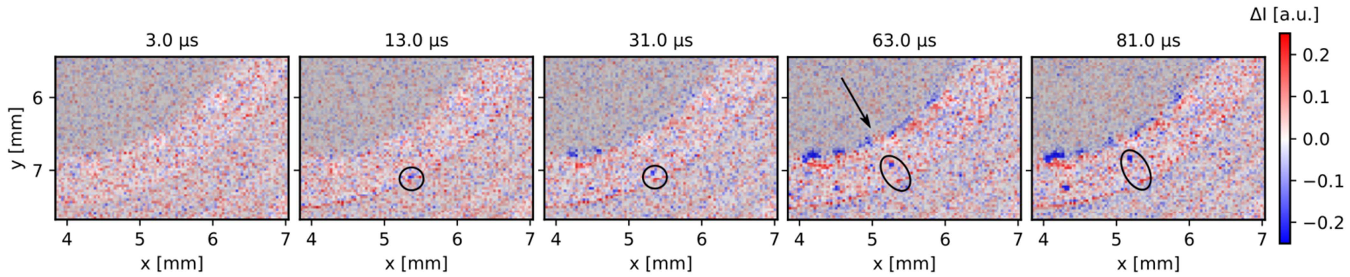

Figure 2. Dynamic of the fastener cavity during current injection for selected delays in a zoomed area from Figure 1b (see red dashed box). The injection starts at $\tau = 0$ µs. The colour bar corresponds to the difference $\Delta I(\tau) = I(\tau) - I(\tau = -1\ \mu s)$, where $I(\tau)$ is the contrast amplitude of the image at the delay τ. For reference, $I(\tau = -1\ \mu s)$ is superimposed on $\Delta I(\tau)$ and is put in transparency (grey background). The circle shows particle ejection, starting around 13 µs and related to arcing. The arrow shows growing damages on the edge of the dowel.

The dynamic of the cavity during current injection is reported in Figure 2. It shows for selected delays a zoomed area from Figure 1b (see red dashed box) since most of the dynamic happens here. This is not surprising because it corresponds to the area with the shortest Ti-CFRP gap. To enhance the spark erosion evolution, we plot the difference $\Delta I(\tau) = I(\tau) - I(\tau = -1\ \mu s)$, where $I(\tau)$ is the contrast intensity of the image at the delay τ. This information refers to the colour bar. To better locate phenomena, it is superimposed on the initial image $I(\tau = -1\ \mu s)$ put in transparency (grey levels). Note that $\tau = 0$ µs is the beginning of the current injection. Two dynamics can be seen. Starting around 13 µs, a particle is pulled off from the CFRP and thrown into the cavity (see the circle – particle ejection can be seen in other location but are not shown). On the CFRP side, the persistent red spot indicates a gain in intensity, meaning that matter has been extracting leaving a hole of about 95 µm x 65 µm (along x and y respectively). Considering that this particle ejection happens when the current is at its maximum, it can be related to arcing phenomenon in the cavity. Then, on a slower dynamic, the edge of the dowel (see the arrow) is progressively melted: the molten depth at the interface is ~ 96 µm after 20 µs, until it slowly stablises to ~ 200 µm beyond 50 µs. The damaging evolves similarly than the cumulated electrical energy (E_{cum}) deposited as a function of time in the sample. E_{cum} reaches a maximum of 38 J however, only a fraction of the total electrical energy deposited in the assembly is used to melt the Ti dowel. We can estimate this fraction and the molten thickness with a simplified electro-thermal model of electric contact [2] in fastener assembly. The model assumes that the current is constricted in a definite number *N* of spots which correspond to arc roots connecting the dowel to the CFRP. However, limits need to be imposed on *N* and the spots diameter so that the model is robust. Such limits can be set using the experimental observations. To go even further with the model, a quantitative analysis of the tomographic data will be needed in order to determine the density of spots (number of spots per mm) and the volume of damaged material (both for the fastener and the CFRP). A quick analysis of the tomographic data confirms the assumptions put forward by the high-speed observations. The cavities formed in the CFRP wall are a few tens of µm in size and the molten Ti gives rise to protrusion of about 100 µm on the dowel wall. These create weak points in the assembly where current will be concentrated at the next lightning shock.

<u>Publications arising thus far from this work:</u> a proceeding has been submitted to the International Conference on Lightning & Static Electricity (ICOLSE) 2022 (to be reviewed).

[1] R. Sousa Martins et al., “Characterization of dynamic carbon-metallic contact resistance submitted to a lightning current waveform”, ICOLSE 2019
[2] R. Holm, “Electric contacts: theory and applications”, Springer Verlag GmbH, fourth edition, 1967