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Monitoring the Dismantlement of Four Flying Buttresses

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ABSTRACT: The church of Saint-James is situated in Leuven (Belgium). In 1995, a stability study showed that the condition of its flying buttresses gave cause for serious concern. In 2000 it was decided to dismantle them. Tie-rods were placed in two sections of the nave and four flying buttresses were dismantled. This intervention created the unique opportunity to place load cells on the tie-rods and to monitor the forces during and after the works.

1 SAINT-JAMES CHURCH

Saint-James church is a building with a complex history, with parts dating from the 13th to the 19th century (Schueremans and al. 2006a, Fig. 1). It is built in a swamp area, at the bottom of a valley. Following each of its extensions, the church suffered important differential settlements.

The critical intervention happened at the turn of the 15th to 16th century when the original wooden roof of the nave was dismantled, the walls heightened by about 8.4 m and the space covered by brick vaults (Fig. 1). This new surcharge (more than 500 kN for each column of the nave) lead to important new settlements (estimated to more than 10 cm: further details in Schueremans and al. 2006a).

After periods of concern, alterations and partial restorations (traced back in Van Balen 1995), it was decided in 1963 to close the church to the public. Restoration works only started in 1971 but stopped a few months later, before completion. There followed a long period of inactivity. In 1994, the Flemish Community, ordered a study (Van Balen 1995) from the *Raymond Lemaire Centre for Conservation* (K.U.Leuven) to assess the structural condition of the church.

This paper will concentrate on the specific problem of the flying buttresses identified in the aforementioned study. Other structural problems of the church are discussed in two other papers presented during this conference (Schueremans and al. 2006 a,b).

2 FLYING BUTTRESSES

The nave of Saint-James is very peculiar: the thrust of the vaults is resisted by tie-rods in the two Western sections (S2 and S3) and by flying buttresses in the two Eastern sections (S4 and S5) (Fig. 1). Traces visible on the Northern and Southern facades indicate that, at some point, there was an intention to build flying buttresses also on the Western side.

The four flying buttresses were extremely deformed. Following the heightening of its walls, the nave suffered important settlements. This induced important tensions in the flying buttress, as the pier buttresses on which they rested did not experience the settlements of the nave. In consequence, they had to break to accommodate the movements.

Fracture of a structure does not necessarily make it unstable. In order to assess the stability of the church and of the flying buttresses in particular, sections 3 and 5 and all four flying buttresses were surveyed (Van Balen 1995). Photographs were taken with a semi-metric camera (Rollei SLX: 6x6 camera with a reseau plate in the film plane) and a 3D computer model was prepared with the Photogrammetry software *Phidias*.

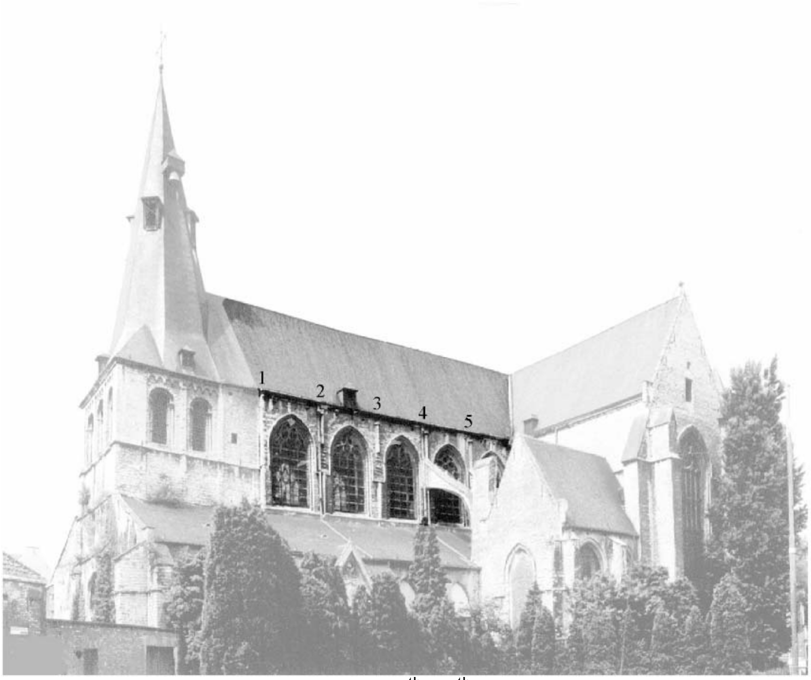

Figure 1 : South Facade, with the 15th-16th century alteration emphasised

The condition of the South-Western flying buttress (FB-4S) was particularly critical (Fig. 2). The arch was not perpendicular to the nave, was not aligned with the pier buttress, presented an important angled bend in its lower part and its masonry was partly loose.

In a structure without any resistance to tension, stability is impossible if no pressure line can be found lying wholly within the geometrical shape of the structure. In the absence of horizontal body forces, the horizontal projection of the pressure line is a straight line. Now, in the case of FB-4S, the best possible line just fitted into the shape, almost touching it at three different places, ready to form a mechanism (it passed at a distance of the order of magnitude of the accuracy of measurement: see Schueremans and al. 2001 to find a discussion of the influence of the accuracy of measurements on stability assessments). The stability of the flying-buttress was therefore very critical. Small movements could have lead to collapse.

The masonry of the flying buttresses had of course a limited resistance to tension but the settlements of the nave had broken it into pieces forming an isostatic structure allowing the movements. It was therefore not safe to assume any resistance to tension.

The 15-16th century intervention also lead to a significant increase of the load acting on the columns of the nave, with average stresses passing from around 1.35 MPa to 2.26 MPa (assuming roofs of similar weight). With those levels of stresses, it is important to have well-centred forces. But, without flying buttresses and vaults on the side-aisles (dismantled during the works in the 1970s), the only horizontal force acting on the walls would have been the thrusts produced by the main vaults, leading to unacceptable eccentricities at the base of the columns.

In the 1995 report, ground was identified as the main cause of the structural problems of the church. But besides long term measures, and following the arguments summarised above, urgent intervention on the flying buttresses was also recommended.

3 DISMANTLEMENT

In 1999 and because of their bad condition, it was decided to dismantle the four flying buttresses and to replace them by provisional tie-rods to secure stability. No decision was taken whether they should be rebuilt in future (with a shape slightly altered in order to get a higher coefficient of safety) or whether they should be replaced by permanent tie-rods. This will be part of a general plan of restoration for the church.

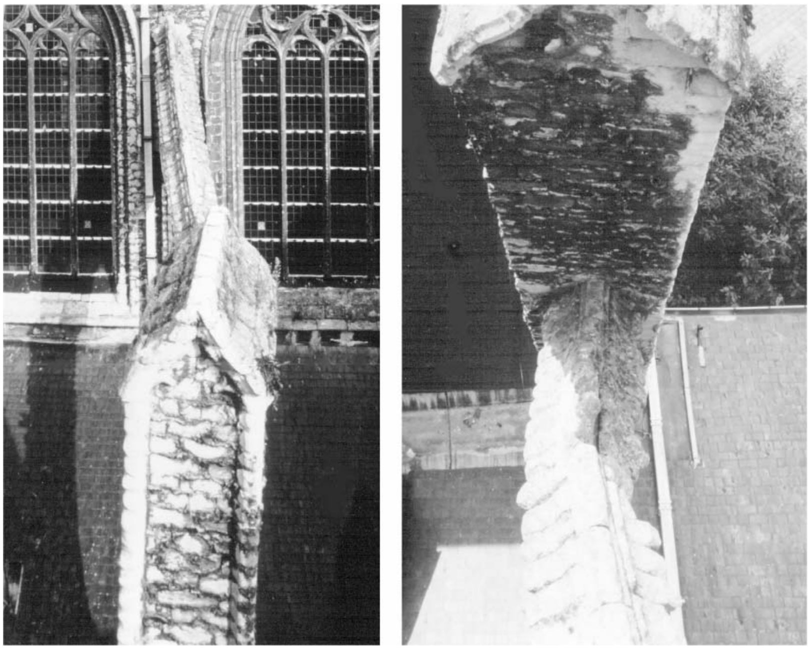

Figure 2 : South-Western flying buttress (FB-4S). Left: misalignment of the structural elements. Right: view from the top of the angled bend in the arch, near the buttress

3.1 Documentation

The stones of the arch were numbered and photographs were taken with a semi-metric camera in preparation of a possible reconstruction of the flying buttresses.

3.2 Tie-rods

In each of the two sections, four tie-rods (Φ 24mm) were placed, two above and two below the contact zone of the flying buttresses with the walls of the nave. They pass through the windows of the clerestory and are anchored on horizontal U profiles, resting on consoles fixed on two vertical I-beams framing the flying buttresses (Fig. 3).

Twenty four days after the beginning of the works, four metallic props were installed at the place where the flying buttresses once stood. This measure was considered necessary by the engineer advising the architect in charge of the works. At the *Raymond Lemaire Centre for Conservation*, we were not convinced of their necessity but were only responsible of the monitoring campaign and the props were installed.

Since then, it is difficult to assess the exact significance of the measurements. Horizontal forces can be transmitted partly through the tie-rods and partly through the props. It has nevertheless to be noted that their behaviour before and after the installation of the props did not change significantly (Fig. 5), which gives us confidence that, at least in the short term, the influence of the props was limited.

3.3 Dismantlement process

After construction of scaffolding and centring, placement of the tie-rods and stressing of the centring, the dismantlement of the flying buttresses started. The general strategy was to try to minimise the movements during the intervention. The distance between the walls was monitored with a *Distinvar* and, when necessary, the force in the tie-rods was increased to limit the deformations (tightening their screws).

Figure 3 : South facade, dismantlement of the South-Western flying buttress (FB-4S).
a: wall top, b: wall, c: voussoir arch

For the distance measurements, reference points installed in 1994 to monitor the displacements of the abutments of the vaults were reused (setup and results of those past measurements are presented in Smars et al. 1998).

The flying buttresses were dismantled in four consecutive days (day 2 to 5), one day for each of them (order: FB-4N, FB-4S, FB-5S, FB-5N). The wall top (Fig. 3.a) was first disassembled, then the wall (Fig. 3.b) and finally the voussoir arch (Fig. 3.c). To be able to dismantle the arch, it was necessary to break one of the voussoirs as the arch was still under compression. The other stones could be removed without damage. The stones are now stored inside the church. If, one day, it is decided to rebuild the flying buttresses, the original stones can be reused and placed in their original position.

4 MONITORING

4.1 Settings

Each of the eight tie-rods was equipped with a load cell; a data logger was placed in the nave with a display giving instant reading and a computer, in the gallery near the tower, was recording the data.

Measurements ran for 56 days, between March 11th (day 0) and May 5th 2000 (day 55). Every 4 minutes (20 minutes between March 28th -day 17- and April 4th -day 24-), two measurements were taken at 4 seconds of interval. In that way, if a measurement did not succeed (which happened occasionally), a second chance was offered to get valid data. March 26th (day 15), daylight saving time began but, for consistency, winter time (GMT+1) was used for the whole measurement period.

4.2 During the dismantlement of the flying buttresses

During the work on the flying buttresses, the forces in the tie-rods and the deformations of the nave were continuously monitored. The tension of the tie-rods was adjusted as necessary. Notes were taken during the works to record the various events.

All four periods of dismantling, are clearly identifiable on the graph (Fig. 4: a-h). It is worth noting that forces increase relatively regularly during the dismantlement and that works on one section had a strong influence on the forces in the tie-rods of the other section.

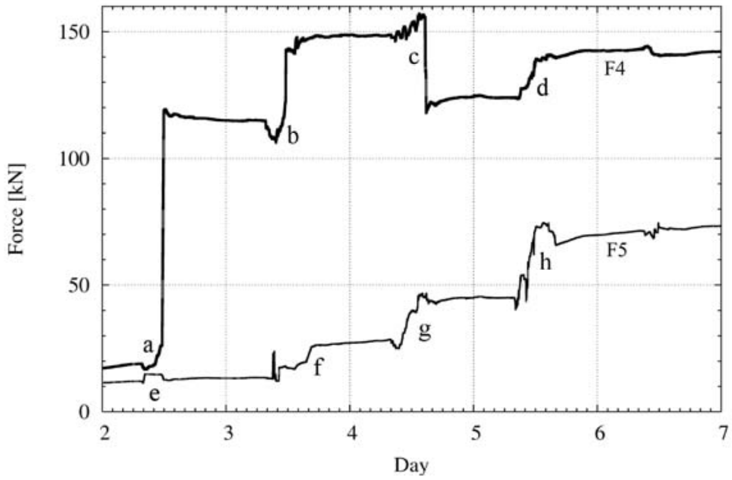

Figure 4 : Forces in the tie-rods during the dismantling of the flying buttresses
F4: sum of the forces in the four Western tie-rods, F5: sum of the forces in the four Eastern tie-rods,
a & e: during the dismantling of FB-4N, b & f: during the dismantling of FB-4S,
c & g: during the dismantling of FB-5S, d & h: during the dismantling of FB-5N

Sudden changes (Fig. 4: a, b, c) correspond to turns of the tie-rods screws. The strongest increase happened at the end of the dismantling of FB-4N, when the screws were tightened up by about 3/4 of a turn (2mm) (Fig. 4.a). The forces increased by 92.5kN (which is consistent with a deformation of 2mm of the four tie-rods). But the displacement of the walls, measured by the Distinvar, was only 0.29 mm. The drop in *c* is the result of an attempt to balance the forces in sections 4 and 5. During the intervention, the maximum displacement was 0.86 mm in section 4.

4.3 After the dismantlement of the flying buttresses

The total force in section 4 (*F4*) is in average about two times higher than in section 5 (*F5*) (Fig. 4, 5). In section 4 the tension is higher in the upper tie-rods but in section 5 it is higher in the lower tie-rods. These facts are not very surprising; forces in the tie-rods are very sensitive to small differences of pretensioning.

4.4 Influence of temperature

As can be seen on Fig. 5, forces in the tie-rods decrease when temperature increases. Between day 8 and 47, the average outside temperature increased by more than 10°C. If the walls were rigid, this would correspond to a reduction of forces in the tie-rods of more than 45 kN. In reality, the observed reduction was much smaller: about 20 kN. The following paragraphs explore possible reasons for such a discrepancy.

An increase of temperature produces an extension of the tie-rods. If the walls were perfectly rigid, the tension would decrease. In reality, the distance between the walls will increase until a balance is found between forces produced by walls and vaults (outward forces) and force in the tie-rod.

The force F_T in a tie-rod depends on the variation of distance between the walls x (positive when the vault opens) and of the variation of temperature T.

$$F_T(t) = EA\left(\frac{x(t)}{l} - \alpha T(t)\right) \equiv k_T x(t) - b_T T(t) \tag{1}$$

where l is the length of the tie-rod, A its cross-sectional area, E the modulus of elasticity of steel and α its coefficient of thermal expansion. The forces F_V exerted by vault and wall on the tie-rod can be expressed as the sum of a constant term H (which would be the only one if the vault was isostatic), of two terms depending of x and T through two unknown parameters k_V and b_V, (similar to k_T and b_T) and of a term taking into account the possible influence of the speed of variation of x on the reaction of the structure. Indeed, fast changes are likely to produce direct reaction of the structure and slower changes may lead to some relaxation of the forces produced by the masonry structure.

$$F_V(t) = H - k_V x(t) + b_V T(t) - c\frac{\mathrm{d}x(t)}{\mathrm{d}t} \tag{2}$$

where c is a damping coefficient.

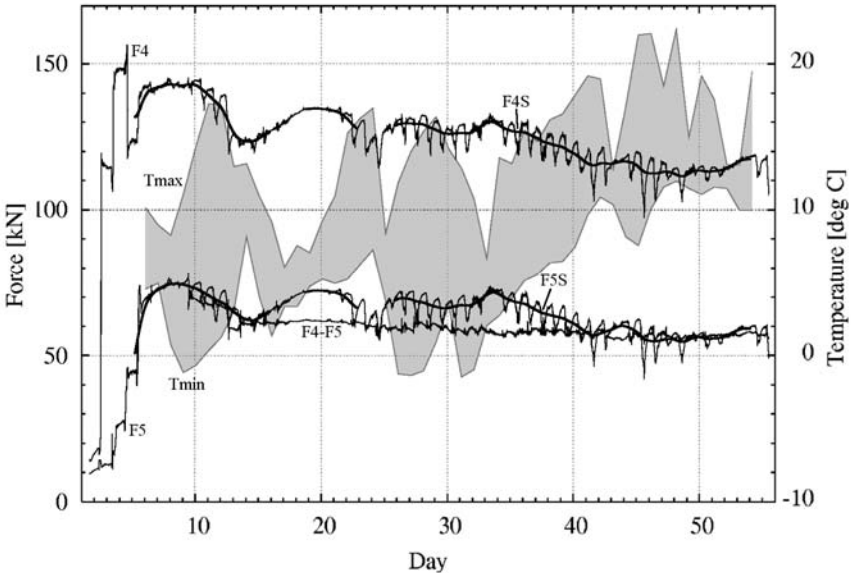

Figure 5: Forces in the tie-rods of section 4 (*F4*) and section 5 (*F5*);
smoothed signals: *F4S, F5S*; exterior temperatures: daily minimum: *Tmin*, daily maximum: *Tmax*

Equilibrium of the structure requires that $F_T = F_V$. To study the influence of the variations of temperature, it is not necessary to consider the constant term H which can be eliminated from the equilibrium equation through a change of origin for x. This leads to a differential equation of the form

$$\dot{x}(t) + \omega x(t) - \beta T(t) = 0 \tag{3}$$

with $\omega = (k_T+k_V) / c$ and $\beta = (b_T+b_V) / c$. If the temperature varies periodically ($T = T_0 e^{i\gamma t}$) and if $x(0) = 0$, the solution of Eq. (3) is

$$x(t) = \beta T_0 \frac{e^{i\Phi}}{\sqrt{\omega^2 + \gamma^2}}\left(e^{i\gamma t} - e^{-\omega t}\right) \tag{4}$$

where Φ is an angle of phase with $\tan \Phi = -\gamma / \omega$. Putting the value of x taken from Eq. (4) into Eq. (1), the force in the tie-rod can be computed. After fading of the transient term $e^{-\omega t}$, it becomes:

$$F(t) = EA\alpha T_0 e^{i\gamma t}\left(\frac{\beta}{\alpha l}\frac{e^{i\Phi}}{\sqrt{\omega^2 + \gamma^2}} - 1\right) \tag{5}$$

If $b_V \ll b_T$, which is very likely, this equation can be simplified to

$$F(t) = -EA\alpha T_0 e^{i\gamma t}\left(1 - \frac{k_V}{k_T + k_V}\frac{e^{i\Phi}}{\sqrt{1 + \left(\gamma/\omega\right)^2}}\right) \tag{6}$$

The first term of Eq. (6) corresponds to a situation with rigid walls. The second term shows that, when the wall-vault structure is flexible, the effects of the variations of temperature are attenuated [up to a factor $k_V / (k_T + k_V)$]. Very high frequencies of variation of temperature γ lead to no attenuation.

In the particular case of Saint-James, the factor of attenuation $k_V / (k_T + k_V)$ is about 0.45. Unfortunately, the temperature data are not of the same quality as the force data. The thermometer installed inside the church did not work as expected and data from weather station and temperature measurements made a few years before had to be used. In future, it would be interesting to place new thermometers at the level of the flying buttresses and to monitor temperature and forces for some time in order to find better estimates of the parameters of correlations.

4.5 Daily variations

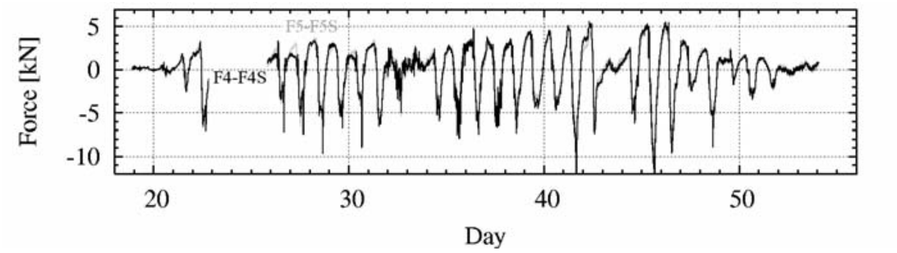

Figure 6: Daily variations

After the dismantlement of the flying buttresses, daily variations were weak during some periods (days 6-8, 13-20, 43, 51-53) and stronger during others periods. The period with the smallest variations of temperature (days 13-20) corresponds to the period with the smallest variations of forces. To separate trends from daily variations, the signal (*F*: *F4, F5*) was convolved with a Gaussian kernel (σ: ½ day) to get a smoothed signal (*FS*: *F4S*, *F5S*) (Fig. 5) and daily variations (*F4-F4S*, *F5-F5S*) (Fig. 6).

$$FS(t) = \int_{-\infty}^{\infty} F(u) \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(t-u)^2}{2\sigma^2}} \mathrm{d}u \tag{7}$$

Fig. 6 shows that daily variations in section 4 and 5 are nearly identical. The average daily variations have a standard deviation of 2.59 kN for *F5* and 2.84 kN for *F4*.

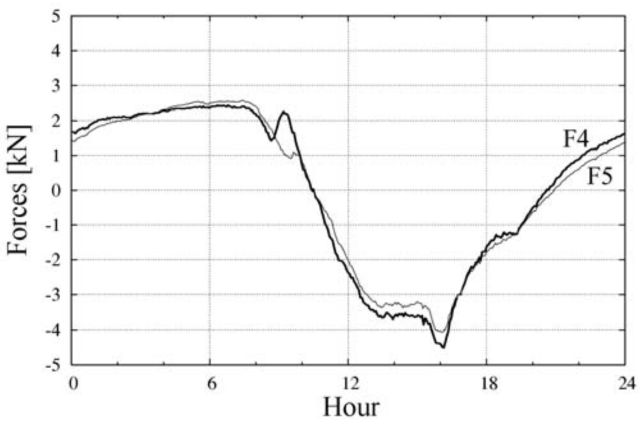

Figure 7: Average pattern of the daily variations of forces

In periods of strong variations, the forces can change by 15 kN in one day. This would correspond to variations of temperature of about 3.3 °C if the walls were rigid and of 7.3 °C. using the same factor of attenuation (0.45) as for the long term variations. In 1995, outside and inside temperatures were measured for a period of six months showing that inside variations of temperature were on average one third (1:3.6) of the outside variations. Inside measurements were made in a zone always staying in the shadow and variations of temperature at the level of the tie-rods are certainly higher. The value of 7.3 °C. is therefore consistent with the maximum daily variation of outside temperature: 17 °C.

There is some regularity in the way forces change during the day. In order to identify a pattern, forces were averaged over a period of 28 days (starting April 4th). On Fig. 7, it can be seen that forces decrease during day time and increase during night time. They are decreasing quite fast from about 8:00 to about 16:00, then slowly recover their original level. During that period, the sunrise changed from 06:14 to 05:16 and the sunset from 19:16 to 20:01.

F5 and *F4* have very parallel evolution (Fig. 5). The standard deviation of the daily variations around a smoothed signal is 0.59 kN (more than 4 times less than the standard deviation of *F5* and *F4*). Nevertheless, there is a trend: the difference *F4-F5* decreases slowly (Fig. 8).

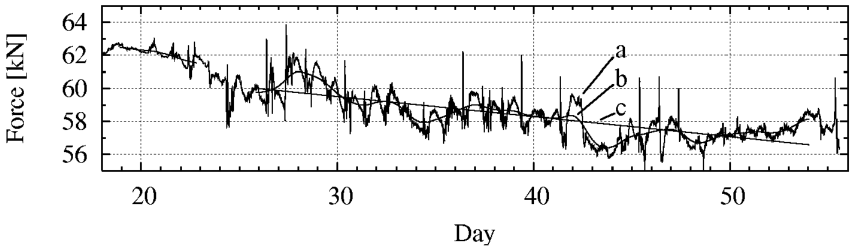

Figure 8: a: *F4-F5*: differences between forces in the Western and Eastern tie-rods, b: smoothed signal, c: linear regression

5 CONCLUSIONS

The critical condition of the flying buttress of Saint-James required a strong intervention. When the difficult decision to dismantle them was taken, a monitoring system was devised with load cells on the provisory tie-rods and provisions to measure the deformations of the vaults abutments.

Thanks to this monitoring system, the dismantling was controlled in real-time and the disturbance on the structure kept to a minimum. This operation was also an opportunity to test a methodology of controlled intervention (Smars 2000, ICOMOS 2003) which is likely to be used in future, when the shoring inside the nave (a huge metallic structure built during the restoration works in the 1970s, Schueremans and al., Fig. 2) will be dismantled.

In addition, it was a unique opportunity to measure forces in tie-rods for a longer period and to study their evolution.

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