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Efficiency of CFRP Strengthening of Arches Tested by Failure of Historical Building after the Inappropriate Repair Intervention

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Abstract This paper should be treated as continuation of considerations placed in the paper (Ciesielski et. al. 2004), where a strengthening of cracked masonry arches, based on CFRP laminates anchored in the brick walls, was presented. The efficiency of CFRP strengthening was tested by a sudden failure of the building caused by inappropriate repair intervention in fundaments and supported soil. Work of the arches strengthening survived the structure from catastrophic consequences. In the paper the failure process is reported and measurements of settlement and cracks width changes are presented. The rescue intervention in the cracked building is also described.

Keywords: Masonry arches and vaults, CFRP strengthening, testing of repair efficiency

Introduction

Being an expert in a case of repair of historical masonries an engineer has to be like a detective. It is necessary to investigate very deeply and carefully all historical and structural aspect of the damaged monument. Past reconstructions or repairs can change totally the scheme and rules of the structural work. The assumption that the structure works as simple as looks like is dangerous path because it can cause new damages or more catastrophic consequences during repair intervention. Experts have a lot of different tools allowing finding deep knowledge about repaired structure. Unfortunately, they use them rarely because of high cost or most often because of lack of enough time for investigation, and in such case experience and critical looking into a problem are very important aspect. If it is a must to repair unknown damaged monument quickly, the rule of minimum intervention should be use to protect the object, as it was done in the case of the historical masonry presented below.

History of Damages Appearance in Heritage mMasonry Building

An old masonry building from the beginning of the XVII century is situated in the centre of Cracow in Poland. The damaged part of this building named West Wing is founded on the border of the strongly consolidated formation of the Prądnik cone and organic soils of flood terrace. Historically localized defense borough of the Okół passed directly under the West Wing (Fig. 1). Structural system of the building was described in (Ciesielski et al. 2004).

Damages of the West Wing were caused by the structural reconstruction in the sixties of the XX century. Changes consisted in removal of some transverse bearing walls on two upper floors (to increase cells for politics prisoners during communism) and the appeared large openings were covered with flat brick arches negligibly executed, which supported cloister vaults (Fig. 1). The introduced changes were resulted in decreasing transverse stiffness of the building and thus in increasing of dead weight loading of soil under outside wall.

It counteracted huge uneven settlement of the West Wing because of weak layer of soil (peat) under foundation (Fig. 1). A trace of the past failure is visible in permanent vertical deformation of the masonry support of a rafter framing covering the structure (Wolski et al. 2006). Settlements investigated by geodesic measurements showed level differences of over 10 cm between the outside and interior walls caps (Fig 2a).

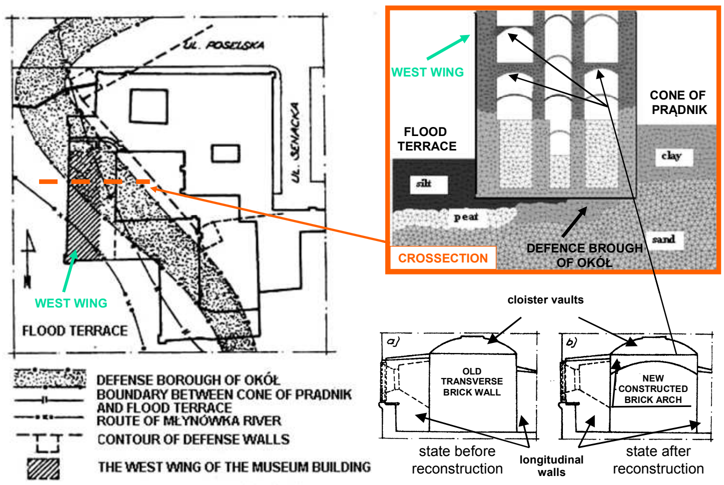

Figure 1: Location of the West Wing and states before and after reconstruction - (after Ciesielski et al. 2004)

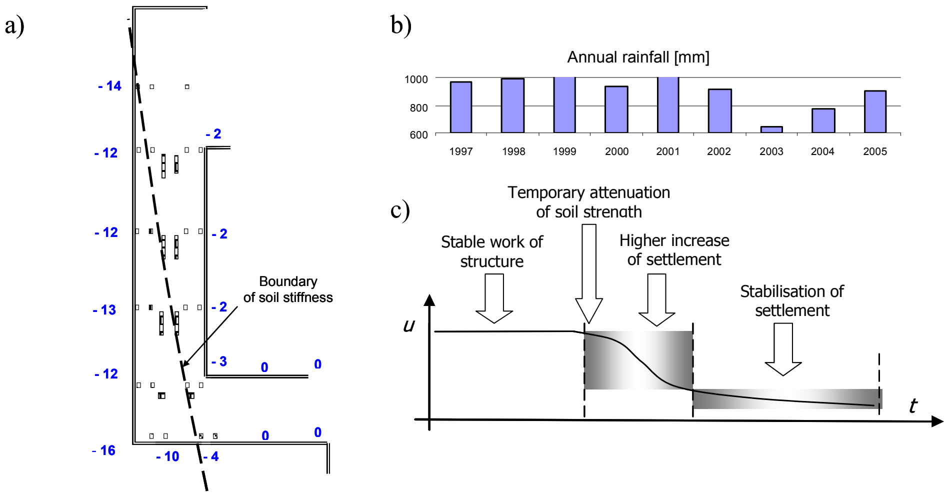

Figure 2: Distribution of settlement values (in cm) at caps of masonry walls of the West Wing (a), annual rainfall in Cracow in years 1997 – 2005 (b) and scheme of settlement process (c) - (after Wolski et al. 2006)

Additionally introduced horizontal forces caused by arches construction, resulted in strutting of the longitudinal bearing walls, increasing thus appeared damages. Cracks and fissures went through vaults, arches and walls of the building. The global damage of the structure occurred rapidly and was quite huge. The real cracks in vaults, arches and walls (uncovered under plasters during inspection in the year 2003) had width of 2 - 45 mm. After stabilization of settlement and redistribution of stresses in the structure, wide cracks were filled with mortar and a new thick layer of plaster was put on the walls and vaults to mask deformations. The cracks have been reoccurred under thermal changes (reaching up to 2 mm width) for the latest 40 years (their distribution is presented in Fig. 5).

First investigations carried out by experts from the Cracow University of Technology were lasting for over 2 years (1996-99). The final conclusion from observations was that the damaged structure works stable according to settlement (Fig. 4 – up to data 19.03.99) but cracks width were changing with temperature fluctuation causing growing trend of crack opening. Dynamism of this process threatened with loss of stability of arches and vaults, supported by strutting longitudinal walls (Fig. 5 – up to data 19.03.99). Strengthening of arches was projected in the year 1999 and constructed in the West Wing in the year 2002. It had to join the longitudinal bearing walls and cracked arches to allow them carry additional horizontal loads from thermal wall movements and from potential loads

following possible new damages. The applied reconstruction method had not introducing additional forces in the historical structure but protecting the object against additional factors, which could affect the existing rather stabile state of the structure. Minimum intervention in the building elevation and structure was an essential factor. The arches (noted as A-E in Fig. 5) were strengthened using CFRP laminates S512 (Fig. 3). Details of material properties and construction process were presented in (Ciesielski et al. 2004). Applied strengthening system is one of the first solutions of this type adopted to a historical masonry structure in Poland.

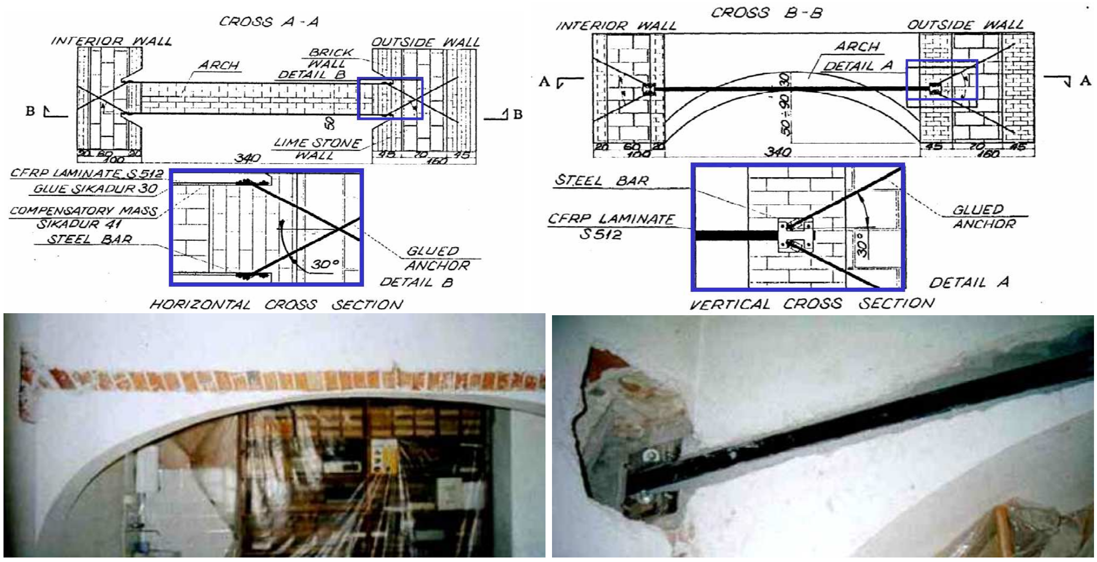

Figure 3: Strengthening of arches in the West Wing - (after Ciesielski et al. 2004)

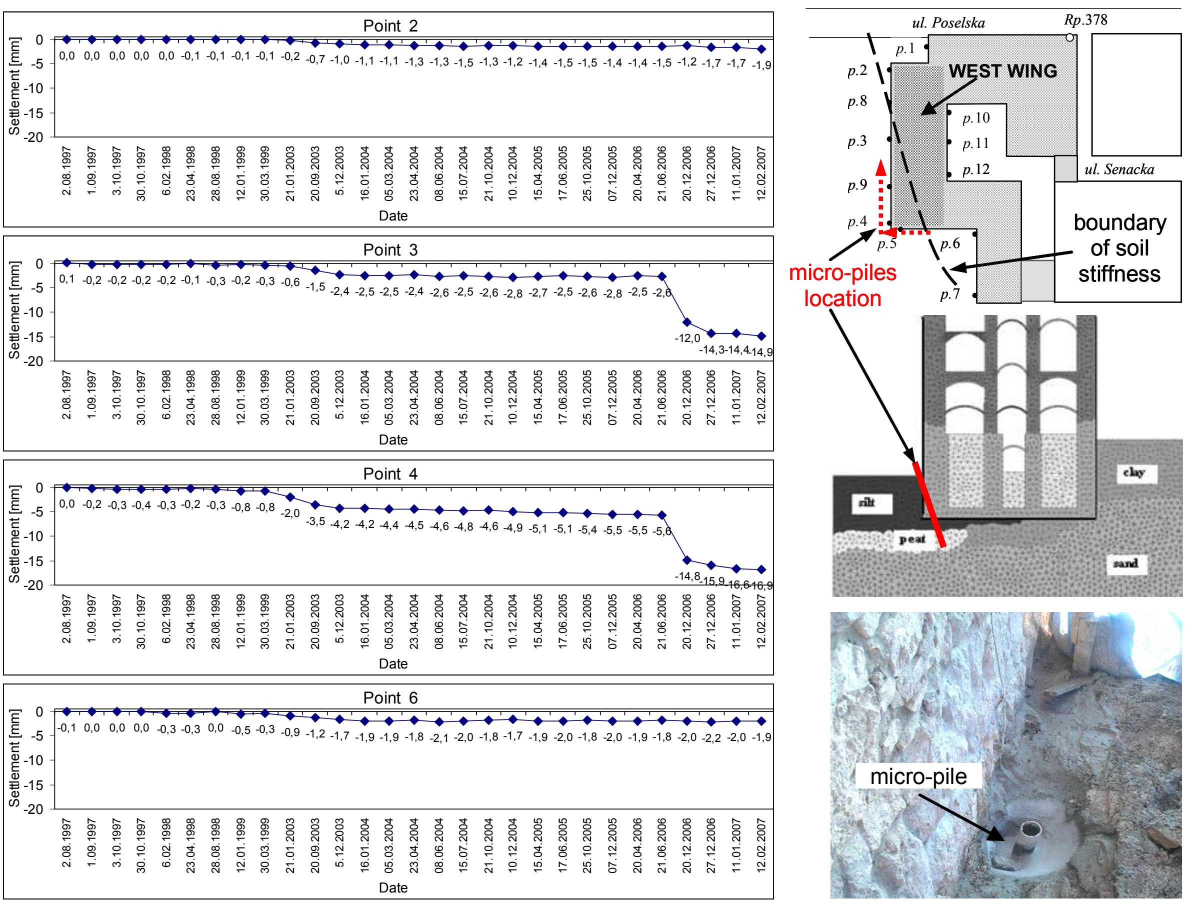

Figure 4: Settlement of the West Wing in the period 1997-2007 and location of micro-piles

The strengthening based on CFRP laminates, anchored in the brick wall by use of glued in steel anchors, permitted for a quick, effective, and relatively inexpensive protection of the damaged part of building. Application of CFRP laminates permitted also to include the strengthening into full co-operation without the introduction necessary of pre-stressing (using of steel bars), which could influences negatively the damaged object being in a relative state of balance.

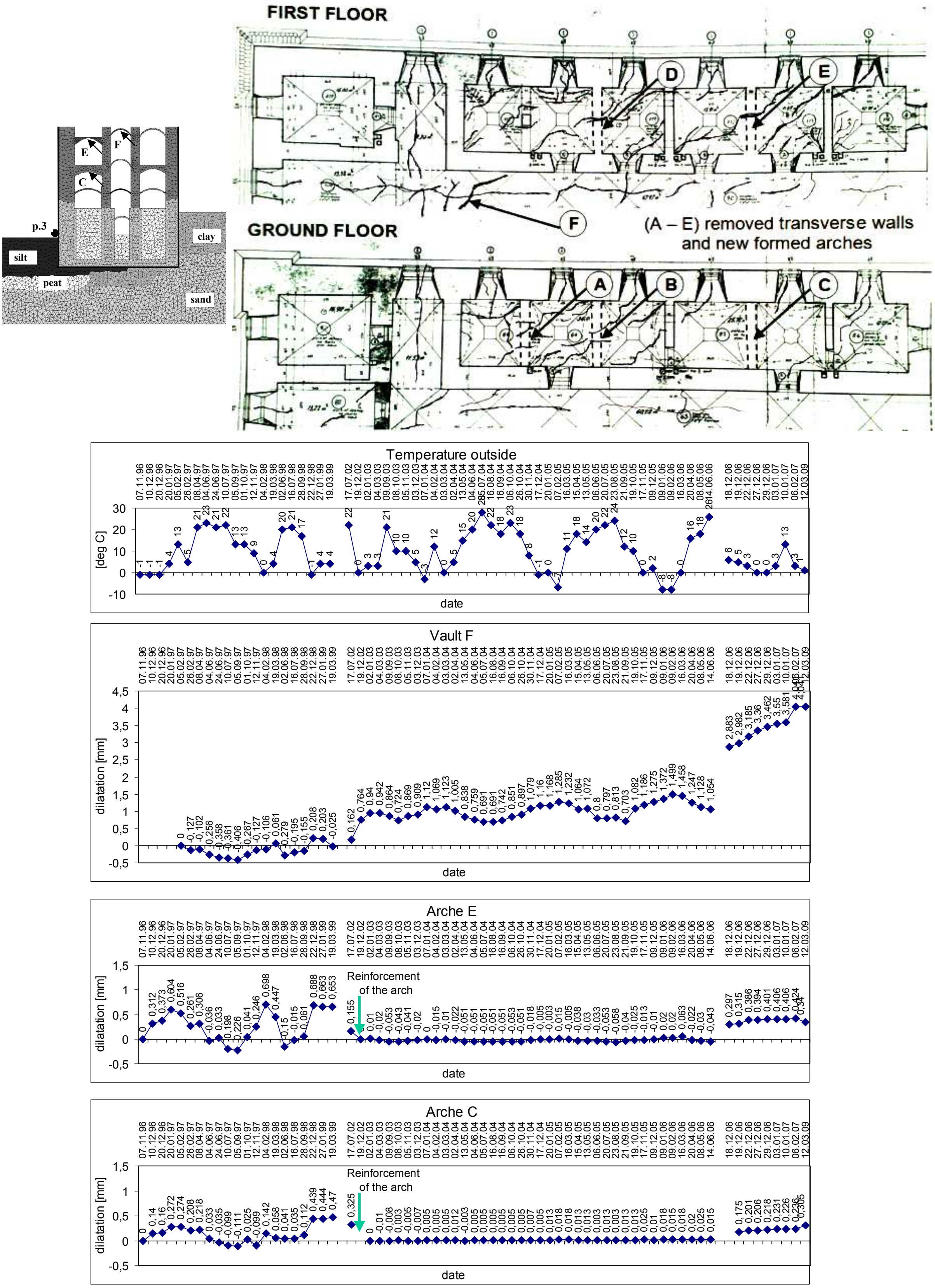

Figure 5: Changes of dilatation of fissures and cracks at the vault F and the arches C and E

Over four year’s observations of changes in the width of fissures in repaired arches showed that the strengthening worked properly according to the designers’ expectations. There was not observed any increase of fissures dilatation at arches (C and E in Fig. 5) after increase of settlement in the period 1999-2006 (Fig. 4), when such increase was observed at vaults (F in Fig. 5) caused simultaneously by settlement and season temperature changes (Ciesielski et al. 2004, Flaga 1998). The reason of small settlement in the period 1999-2002 was lowering of ground water level during constructing of a deeply founded hotel (at the distance of 400 m from the West Wing), but meaningful settlement in summer 2003 was caused by drought in Cracow with a consecutive stabilization after spring rainfalls in the year 2004 (Fig. 2b, 2c). One exception is observed in the case of the West Wing corner (point 4 in Fig. 4), where small permanent settlement appears, caused by the damaged drainage and sewage system, breaking foundation stability in weak soil layer build of peat (Fig. 1).

Worrying changes of crack dilatation in vaults and also observed character of damages and deformations forced realization of vaults structure inspection. It showed necessity of rapid repair of some cracked vaults, because they were about to collapse (bricks were kept in some places only by thick layer of plaster). Two kinds of minimum intervention have been applied in years 2003-2005. In the first case, main cracks were filled with PUR foam (in places where such intervention was enough) (Kwiecień 2004), making polymer flexible joint and retaining this way natural dilatation of damaged building (Croci et al. 2000, Kwiecień et al. 2006). In the second one, two vaults (one cloister vault over a room and one cradle vault over the corridors cross-section) were strengthened using of supporting steel frames (Kwiecień 2005), hidden under thick layer of plaster (Fig. 6). Both methods are reversible.

Figure 6: Repair of vaults using of PUR foam and strengthening using of steel frame

Failure of the West Wing after the Inappropriate Repair Intervention

Finishing the expert process in July 2006 (after over nine years of measurements and strengthening of structure with minimum intervention), repair recommendations were given to the investor and the building owner to be realized in following order: repair of the drainage and sewage system around the foundation (first), global stiffening of whole building (second), stiffening of weak soil supported the West Wing foundation (third) and repair of the deformed rafter framing covering the structure (next). This order of repair was obligatory because of weakness of the West Wing structure and risk of stability loss.

Unfortunately, the other way of repair was chosen for realization by the administrative decision body, leaving out the given expert opinion. They decided to strength first foundation using dozens of micro-piles going through limestone foundations and next to stiff the whole structure. This decision caused dangerous results. In December 2006 was started constructing of micro-piles, causing vibration of whole structure (by limestone drilling) and liquefaction of the weak soil under foundation. Application of micro-pals weakened the peat soil layer causing rapid settlement of the building part of value 10 mm in two days (Fig. 4). The settlement started stabilizing up to value of 18 mm after six month (Fig. 2c) after stopping of palling.

Because of this movement, new cracks appeared on vaults and walls up to 2.5 - 3.0 mm width and the old ones opened increasing they width of similar value (see vault F in Fig. 5). Additionally, there

appeared new fissures at the arches, indicating that the support balance of the strengthened arches was upset, generating additional deformation and stress in the CFRP laminates (see arches C and E in Fig. 5) and also in the anchors (Fig. 3). It should be noticed that work of the arches strengthening (Fig. 3) and constructed steel frames (Fig. 6) survived the structure from catastrophic consequences.

Post-failure Work of CFRP Laminates and the Whole Structure

The weakest part of the strengthening system (CFRP laminates on both site of the arch - Fig. 3) is the anchorage in masonry walls, projected for the maximum longitudinal force of 78 kN, which corresponds to stress of 650 MPa for one CFRP laminate (23% of the ultimate strength). After rapid settlement, the fissures at arch E opened up to 0.424 mm (Fig. 5), causing the CFRP strain of 0.42%. Thus the calculated real longitudinal force in the strengthening system was of 82 kN, which overcomes the projected value of 7%. As a consequence, slip of anchors (0.084 mm) of arch E was occurred causing redistribution of stress in arches E and C working on both floors. It is visible in comparison of simultaneous deformations of CFRP laminates of arches E and C. The sum of elongation (Fig. 5 for 06.02.07) equal to 0.660 mm (0.424+0.236) was changed to the sum of elongation (Fig. 5 for 12.03.09) equal to 0.645 mm (0.340+0.305), indicating loss of deformation energy. This stress redistribution was caused by works stiffening the whole West Wing (2007-2009). Stiffening structure consisted of steel ring beams mounted on longitudinal bearing walls at the floor levels, joined transversally using of pre-stressed steel bars. This strengthening structure was hidden under plasters covering the historical building. Actually, the West Wing is stiffened as a box and protected against structural uneven deformations. The repaired rafter framing allowed for adaptation of the space for new utility rooms. A project of soil strengthening is still under construction.

Conclusions

The described case study presents how important is deep recognizing of work specification of damaged historical masonries before repair. Neglecting of knowledge about past behavior of the repaired structure and basing only on very simple signals given by damaged structure can cause choosing of improper repair method and thus can have catastrophic consequences. Repair solutions of minimum intervention applied in the West Wing were examined by unexpected structural failure and showed their efficiency in practical manner. Presented example indicates that such repair methods using of CFRP laminates and steel frames can be taking into consideration in future applications.

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