Influence of pre-strain on fracture toughness of 3rd generation advanced high strength steels

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Abstract. The present work investigates the influence of pre-strain on the fracture toughness of 3rd Generation Advanced High Strength Steels (AHSS). Specifically, a Carbide Free Bainitic (CFB) and a Quenching and Partitioning (Q&P) steel have been studied, the properties of which are crucial for lightweight vehicle construction. Fracture toughness, which is a key parameter for crash performance applications, is assessed using the Essential Work of Fracture methodology. The study investigates the pre-straining states of uniaxial tension, plane strain, and equibiaxial tension in 1.5 mm Q&P and 1.4 mm CFB sheet-form steels of 1180 MPa tensile strength. Overall, Q&P steel demonstrates superior fracture toughness compared to CFB steel. Remarkably, the specific essential work of fracture (w_e) remains unaffected by pre-straining across different strain states. Nevertheless, pre-straining exerts a notable influence on the non-essential plastic work (βw_p) due to the plastic energy consumed during pre-deformation. These results suggest that pre-strain has little or no influence on the fracture properties of AHSS, which is relevant for the design and manufacturing of high crash-performance and safety-related components.

Introduction

3rd Gen Advanced High Strength Steels (AHSS) have emerged as one of the most promising materials for lightweight construction of vehicle structures. Their outstanding mechanical properties combining high strength, high fracture toughness and good formability are the result of their complex multiphase microstructures and the strain-induced transformation of retained austenite to martensite, also known as Transformation Induced Plasticity (TRIP) effect. The TRIP effect is known to be dependent on the stress state and deformation level [1] and, therefore, the strain induced during the sheet forming process may significantly affect the local properties of the final component. It is well known that the presence of martensite in a microstructure increases the yield strength and the tensile strength, while decreases the fracture elongation. Thus, the amount of transformed martensite due to the TRIP effect during cold forming will also change the tensile properties. It is affecting sheet formability, but this change does not inform about part performance as crash or fatigue [2]. Accordingly, anticipating the influence of such pre-deformation on critical in-use properties, such as crashworthiness, is crucial for the safe design of structural and crash-relevant components.

The present work aims to assess the influence of pre-strain on the fracture toughness of two 3rd Generation AHSS for automotive applications. Fracture toughness has been shown to be a good indicator of the impact fracture performance of AHSS and Press Hardened Steels [2,3]. Frómeta et al. [3] established a correlation between the fracture toughness of different AHSS and their crash failure behavior, thus being an invaluable material parameter to estimate crashworthiness at the lab scale. The study investigates the effect of different pre-straining states, namely, uniaxial tension, plane strain, and equibiaxial tension, on the fracture properties of a Quenching and Partitioning (Q&P) and a Carbide Free Bainitic (CFB) sheet steels of 1180 MPa tensile strength.

Fracture toughness characterization is here conducted using the Essential Work of Fracture (EWF) methodology [4]. The EWF is a simple procedure to measure the crack propagation resistance of AHSS sheets and it has been used to understand their cracking performance [2,3,5, 6, 7, 8]. The results for undeformed and pre-strained specimens are compared and discussed.

Materials

The materials analyzed in this study are two 3rd Gen AHSS for automotive applications. Specifically, a Carbon Free Bainitic (CFB) and a Quenching and Partitioning (Q&P) steel of 1.4 and 1.5 mm thickness, respectively

The microstructure of CFB is characterized by a matrix of carbide-free bainite with globular islands of martensite/retained austenite and laths of retained austenite. The Q&P steel presents a matrix of tempered or carbon-depleted martensite with lath-like retained austenite and globular islands of retained austenite/martensite and bainite. Both steel grades have a content of retained austenite of 12-16% as presented by Frómeta et al. [3].

The tensile properties of the two TRIP-assisted steels were determined according to UNE EN ISO 6892-1 in the transverse direction with respect to the rolling direction. The obtained results are presented in Table 1. Both steels show very similar tensile properties.

Table 1 – Mechanical properties of the investigated TRIP-assisted steel grades at transverse direction: thickness, t; yield strength, σ_{YS}; ultimate tensile strength, σ_{UTS}; uniform elongation (elongation at σ_{UTS}), Ag; elongation at fracture (initial gauge length 80 mm), A_{80}; strain hardening exponent between 2 and 4% of deformation, n_{2-4}.

Steel denomination	t [mm]	σ_{YS} [MPa]	σ_{UTS} [MPa]	Ag [%]	A_{80} [%]	n_{2-4} [-]
HF1180 CFB	1.4	987	1216	9.2	12.6	0.11
HF1180 Q&P	1.5	1034	1191	9.2	13.1	0.09

Experimental procedure

EWF tests

EWF tests were performed according to CWA 17793:2021 [7]. DENT specimens of 240 x 55 mm machined in the transverse direction were used (Fig. 1a), this geometry has shown to be the most suitable because the transverse stress between the notches is tensile and there is no buckling [9]. Initial notches were machined by electrical discharge machining. Then, fatigue pre-cracks were nucleated at the notch root following the recommendations of the ASTM E1820 [10]. The cracks were extended about 1-1.5 mm per side (Fig. 1a). EWF tests were performed at a 250 kN universal testing machine, equipped with a digital videoextensometer (Fig. 1b). 5 different ligament lengths (l_0) ranging from 6 to 14 mm were used and about 3 specimens per ligament length were tested. The specimens were tested up to fracture at a constant crosshead speed of 1 mm/min. The load-line displacement was measured by means of the videoextensometer using initial extensometer marks separated 50 mm.

To check that the ligament section is fully yielded before crack initiation and ensure the validity of the EWF measurements, a full field strain analysis was performed on the surface of the ligament area.

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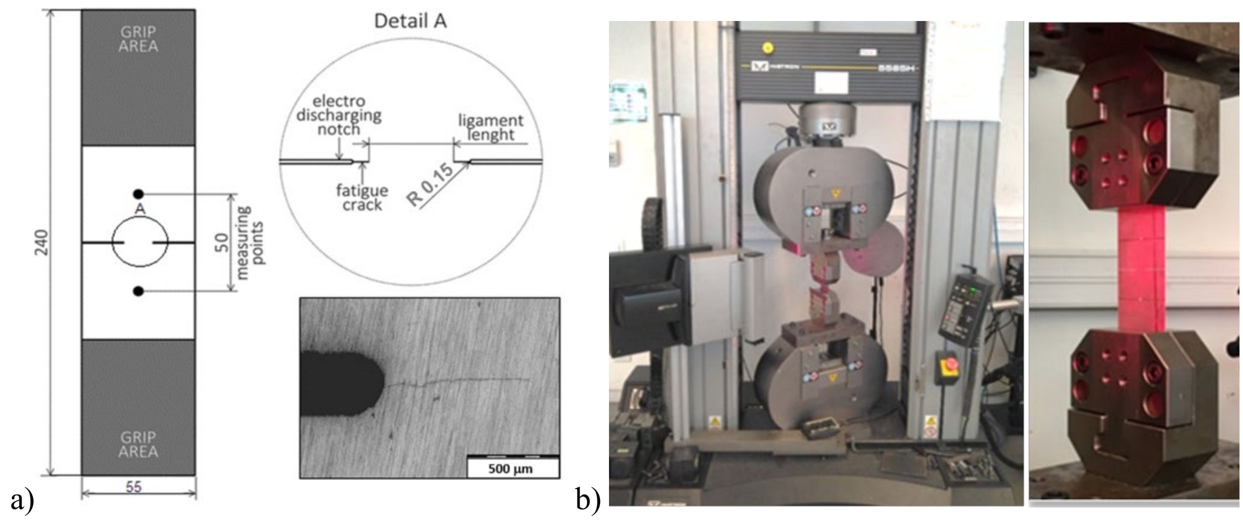

Figure 1 – a) DENT specimen geometry and detail of the fatigue pre-crack at the notch root. b) Universal testing machine used for EWF tests.

Pre-straining

The pre-straining process comprised two methods: uniaxial pre-straining and plane strain/biaxial pre-straining. In the uniaxial approach, rectangular specimens measuring 120 x 45 mm were uniaxially deformed in the transverse direction until the predetermined pre-strain level was achieved at a constant displacement rate of 2.5 mm/min. Subsequently, smaller DENT specimens sized at 70 x 40 mm were extracted from the pre-strained specimens (Fig. 2).

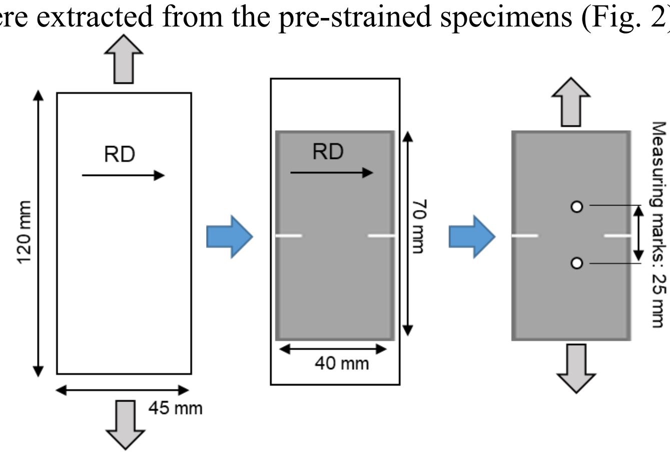

Figure 2 – Schematization of the experimental procedure followed for EWF tests with uniaxial pre-strained specimens.

For plane strain and biaxial pre-straining, Marciniak stretching tests were employed using two different geometries to induce a biaxial and a plane strain state. The pre-strain tests were conducted using an Erichsen machine equipped with a Digital Image Correlation (DIC) system (Fig. 3a). The materials underwent pre-straining up to the specified deformation levels at a punch speed of 67 mm/min, with 15 specimens for each condition. The pre-straining methodology involved stretching one specimen up to fracture while monitoring strain levels with the DIC equipment with a frame rate of 3 Hz. The stage number at which the selected strain level was achieved determined the punch stroke, which was then applied to the remaining specimens. Fig. 3b illustrates a specimen pre-strained in a plane pre-strain condition. After both pre-straining processes, DENT specimens measuring 70 x 40 mm were extracted from the top flat zone of the stretched specimens (Fig. 2).

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From the extracted specimens, fatigue pre-cracking and EWF tests were conducted, with an adjusted load-line displacement length of 25 mm due to the smaller specimen size. The employment of different specimen sizes does not affect EWF results for it describes a local property of the material, as shown by Hilhorst et al. on [11].

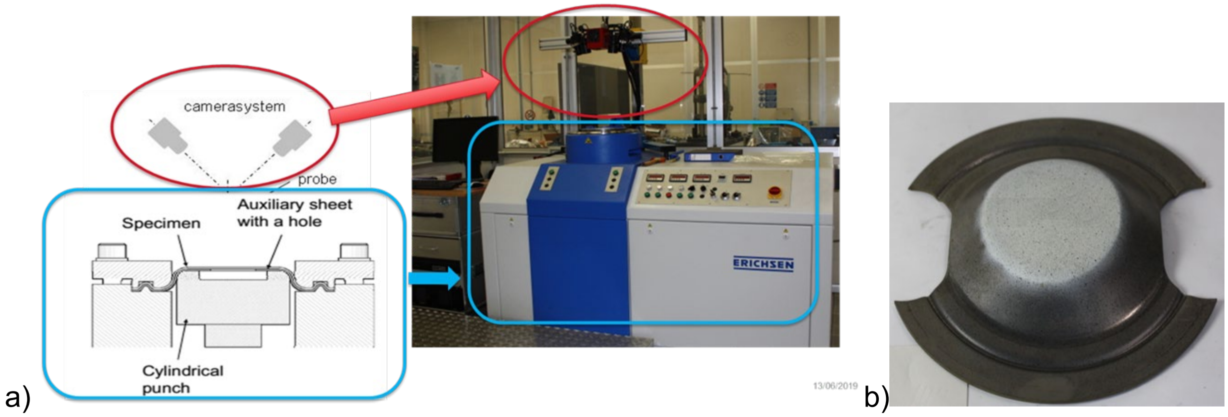


Figure 3 – a) Erichsen equipment and DIC system to perform pre-strain tests at Centro Ricerche Fiat laboratories. b) Pre-strained specimen in plane strain condition.

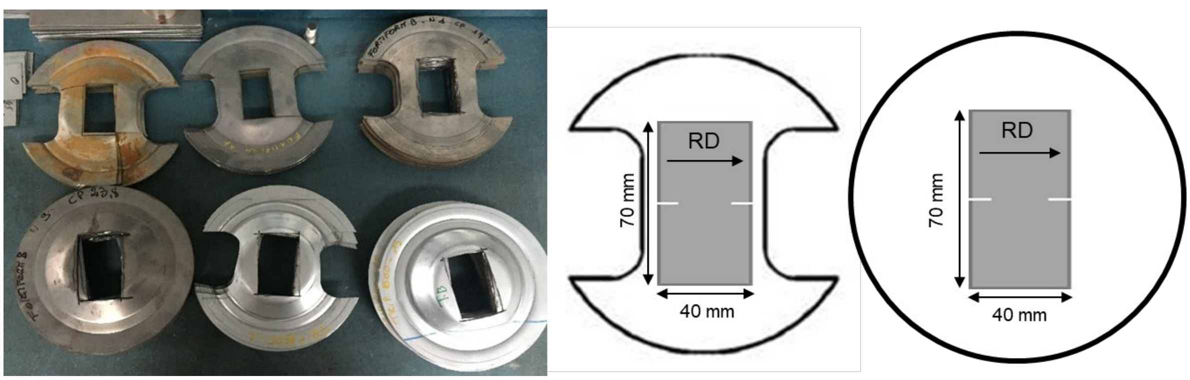


Figure 4 – Extraction of DENT specimens for EWF tests from plane strained and biaxial pre-strained specimens.

Fig. 5 shows the deformation paths followed for specimen pre-straining. The selected pre-strain level was 7.4%, which is also indicated.

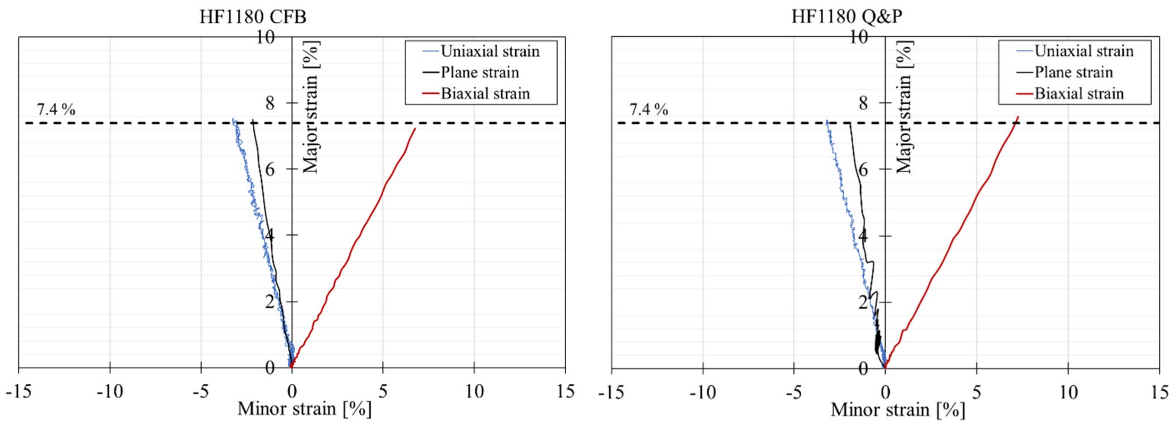
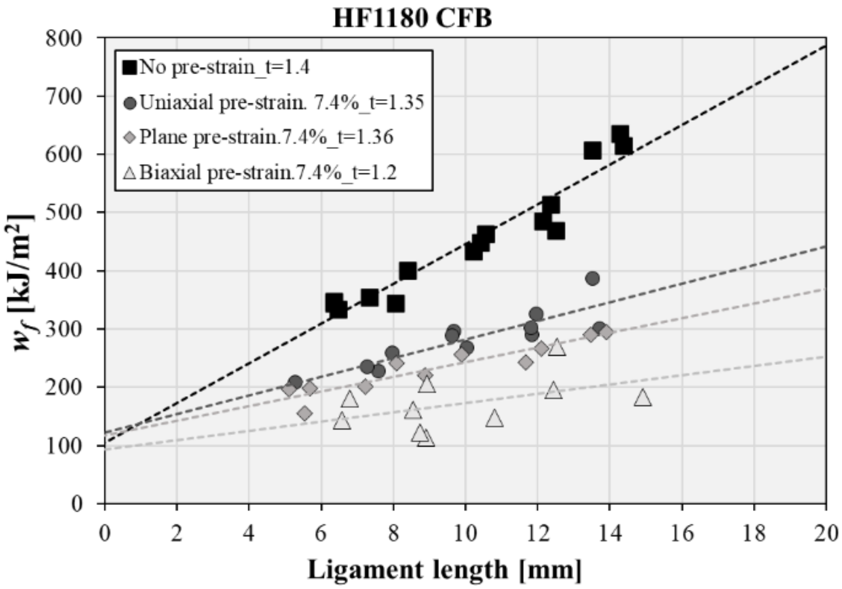


Figure 5 – Deformation paths and strain level selected for pre-straining the specimens.

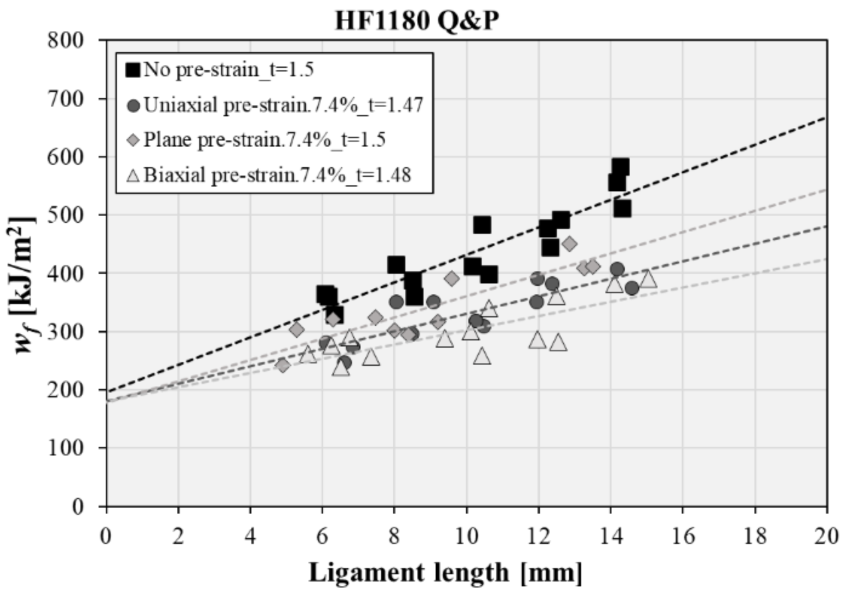
Results and discussion

Fig. 6 presents the EWF results for CFB and Q&P steels in the four pre-straining conditions studied. The pre-straining state and the final thickness of the metal sheet are indicated. In all cases, w_f values escalate linearly with the ligament length. It can be observed that Q&P steel presents higher fracture toughness than CFB. The first remark that can be made is that the pre-straining mainly affects the plastic work, βw_p, obtained by the slope of the linear regression. Also, it can be noted that the linear fitting is good for both materials in the undeformed state ($R^2 = 0.83 – 0.92$). However, the correlation coefficient of the linear regression of the pre-strained states decreased due to the local effects of pre-straining that can be detected experimentally by the application of the EWF methodology; nevertheless, the trend on the linear adjustments is clear.

With the support of a DIC system and a succeeding full field strain analysis of the specimen surface, it was verified that the ligament area is fully yielded before fracture initiation in all the studied conditions, indicating that the EWF methodology is valid to characterize fracture toughness of these materials.



a)



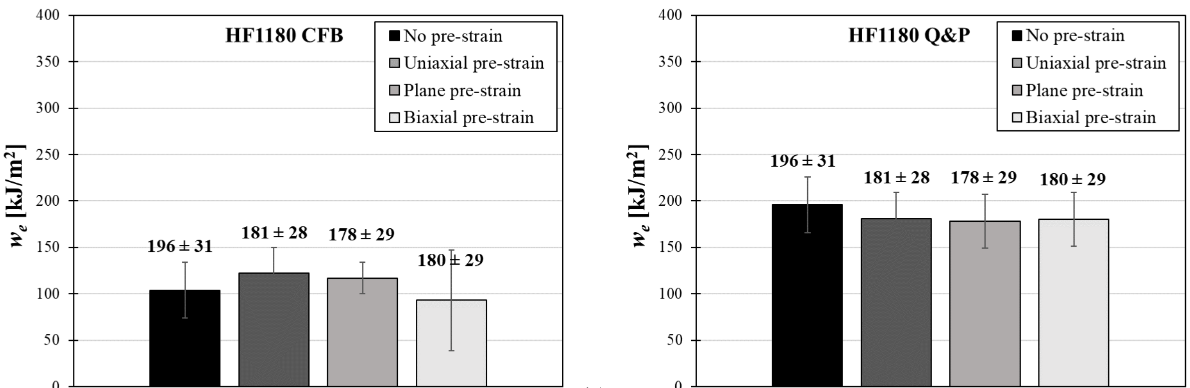
b)

Figure 6 – EWF results for the investigated TRIP-assisted steels investigated: a) CFB and b) Q&P; in the four pre-straining states tested.

Moreover, it can be noted that fracture toughness is different for both steels in the undeformed state, despite the tensile properties being very similar. Results show that CFB presents considerably lower fracture resistance than Q&P. These results are in agreement with previous works [12] underlying that fracture toughness cannot be directly estimated from tensile parameters. Therefore, a proper description of crack initiation and propagation resistance behavior of high-strength metal sheets requires the application of a fracture mechanics approach.

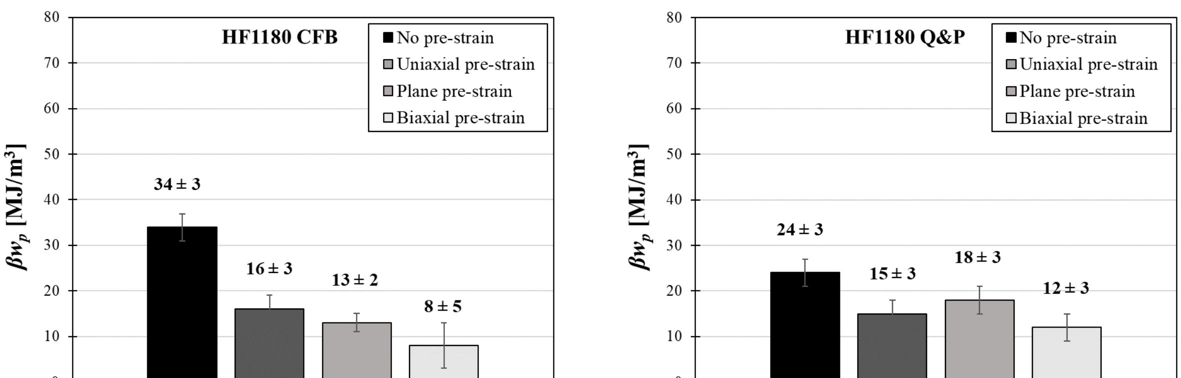
A summary of the w_e and βw_p results for the two tested steels and the pre-straining conditions performed is presented in Fig. 7 and Fig. 8, respectively. It is important to note that the fracture toughness remains constant across the different pre-straining conditions in both TRIP-assisted steels investigated. The energy absorbed for the generation of new fracture surfaces is similar independently of the strain state of the steel sheet. The non-essential plastic work is notably reduced subsequent to experiencing pre-straining. This behaviour is coherent as the pre-straining process consumes plastic work and the remaining plasticity available for the fracture process is reduced.

The study results provide additional detail and depth to the understanding of the parameters influencing fracture resistance mechanisms since very few works are available. Hodges et al. [13] determined by Charpy tests that the global fracture resistance of AHSS was affected by pre-straining. However, it should be considered that such impact tests give the overall fracture energy, without giving information about the energy spent in fracture resistance and the plastic work. The results provided by EWF methodology accurately separate both contributions and permit to readily assess the effect of sheet pre-strain level on the fracture toughness. Since, fracture toughness allows estimating the edge cracking resistance [3] and crashworthiness [2], the results obtained in this work through the EWF method can be used to identify material and processing challenges associated with edge cracking [14] and crash performance of AHSS.



a) b)

Figure 7 – Summary of w_e values in four pre-strain conditions for materials: a) CFB and b) Q&P.



a) b)

Figure 8 – Summary of βw_p values in four pre-strain conditions for materials: a) CFB and b) Q&P.

Conclusions

The present investigation on the effect of pre-straining in the fracture resistance of two TRIP-assisted 3rd Gen AHSS steels has provided the following significant findings:

a) The EWF methodology has shown to be applicable to characterize the fracture toughness of the two AHSS investigated in four different strain states.

b) Q&P steel exhibits superior overall fracture toughness compared to CFB steel.

c) Pre-straining presents a significant effect on the non-essential plastic work, βw_p.

d) Biaxial pre-straining presents the greatest reduction on non-essential plastic work.

e) The specific essential work of fracture, w_e, remains unaffected by pre-straining across all investigated strain states.

f) Accordingly, crash performance and edge cracking resistance are not expected to be greatly affected by sheet pre-straining during cold forming.

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