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Procedia Structural Integrity 13 (2018) 728–734

Structural Integrity Procedia

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ECF22 - Loading and Environmental effects on Structural Integrity

Fatigue behaviour of additively manufactured polylactide (PLA)

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Abstract

Additive manufacturing (AM) is a group of fabrication techniques through which materials are joined, usually layer upon layer, to make objects from three-dimensional virtual models. Owing to its unique features, this disruptive technology is set to transform the way designers across all engineering disciplines engage with manufacturing. Since this fabrication process affect the way materials behave under static, dynamic and time-variable loading, it is evident that the mechanical performance during in-service operation of AM materials must be studied in depth in order to effectively de-risk their usage in situations of engineering interest. Not only by running appropriate experiments, but also by re-analyzing a number of data sets taken from the literature, the present paper investigates the influence of raster orientation as well as of non-zero mean stresses on the fatigue behavior of AM polylactide (PLA). PLA is biodegradable polymer that can be 3D printed easily and at a relatively low cost. As far as objects are manufacture flat on the build plate, the results being obtained suggest that: (i) the effect of the raster direction can be neglected with little loss of accuracy; (ii) the presence of non-zero mean stresses can be modelled effectively by simply using the maximum stress in the cycle.

Peer-review under responsibility of the ECF22 organizers.

Keywords: Additive manufacturing; polylactide (PLA); fatigue; mean stress effect, raster orientation

1. Introduction

AM brings promise of a new industrial revolution by offering the capacity to manufacture parts through constant deposition of material layers directly from numerical models. Designers can achieve many intricate and complex geometric designs which would fall short on traditional processes. Thanks to its unique features, in the near future AM is expected to lead to new design paradigms that can result in components characterized by superior in-service performance and manufactured by reducing the usage of natural resources and energy. Further, the use of AM could result in quicker ways to make repair of expensive and/or rare parts, to manufacture in remote locations, and to fabricate customized parts on demand. However, to fully exploit this enormous potential, the mechanical behavior of

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2452-3216
Peer-review under responsibility of the ECF22 organizers.
10.1016/j.prostr.2018.12.121

AM components and structures and their structural integrity need to be understood and fully characterized to avoid un-wanted failures during in-service operations. The key sectors that will benefit immensely from such understanding include, amongst others, aerospace, biomedical and automotive industries.

Nomenclature

k	negative inverse slope
N_f	number of cycles to failure
N_0	reference number of cycles to failure ($N_0=2\cdot10^6$ cycles to failure)
P_S	probability of survival
R	stress ratio ($R=\sigma_{min}/\sigma_{max}$)
T_σ	scatter ratio of the endurance limit for 90% and 10% probabilities of survival
θ_f	orientation of the additively manufactured filaments
σ_a	stress amplitude
σ_A	endurance limit at N_0 cycles to failure (in terms of stress amplitude)
$\sigma_{A,R=-1}$	endurance limit at N_0 cycles to failure (in terms of stress amplitude) under R=-1
σ_m	mean stress
σ_M	mean stress extrapolated at N_0 cycles to failure for a given value of R
σ_{max}	maximum stress in the fatigue cycle
σ_{MAX}	endurance limit at N_0 cycles to failure (in terms of maximum stress in the fatigue cycle)
σ_{min}	minimum stress in the fatigue cycle
σ_{UTS}	ultimate tensile strength

PLA is a biodegradable thermoplastic polymer that is obtained from renewable sources such as corn starch or sugarcane. Thanks to its physical properties, PLA can be manufactured very effectively and at a relatively low cost by using commercial 3D-printers, with Fused Deposition Modeling being the most common technology that is used to manufacture objects of PLA. Owing to the important role this AM material is expected to play in situations of practical interest, the present paper investigates the fatigue behavior of AM PLA by post-processing a large number of data both generated by running *ad-hoc* experiments and taken from the technical literature. In particular, attention will be focused on the way raster orientation and non-zero mean stresses affect the overall fatigue behavior of AM PLA.

2. Effect of the manufacturing direction

As far as polymers are concerned, the so-called Fused Deposition Modelling (FDM) is one of the most common and, therefore, mature AM technologies that is available in the market. Via FDM, objects are manufactured by using a nozzle to melt threads of plastic material that are unwound from a coil. The filament extruded through the nozzle is then deposited directly onto the build plate to create a layer of material. The wanted shape for each layer is obtained by making the extrusion nozzle move horizontally over the built plate itself. As the thin filaments being deposited cool and harden, they bind not only to each other, but also to the previous layer of material. As soon as a layer is completed, the build plate lowers so that a new layer can be fabricated. Another important aspect is that, before starting manufacturing a new layer, 3D-printers first build up a perimetric wall (called "shell") that is designed to retain the internal material. To prevent the formation of voids and manufacturing defects, the thickness of the shell is usually taken equal to a multiple of the nozzle diameter. Thanks to the role played by the shell, the density of the bulk material can then be changed, with this allowing objects' weight and material's usage to be reduced/optimized.

According to the manufacturing process briefly described above, even if the in-fill level is set equal to 100%, the orientation of the internal filaments can vary, with this resulting, in terms of meso-structure, in an anisotropic bulk material. In this context, the first important aspect is understanding whether the raster direction affects the overall fatigue behavior of 3D-printed PLA. In order to investigate this key issue, a number of experimental results were taken from the technical literature, with these data being generated by testing un-notched specimens fabricated by making manufacturing angle θ_f vary in the range 0°-90° (see Figure 1 for the definition that is adopted in the present investigation for angle θ_f).

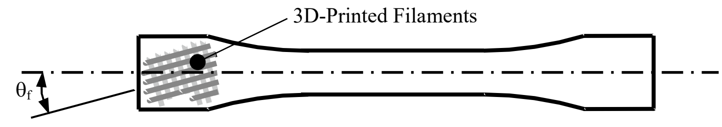
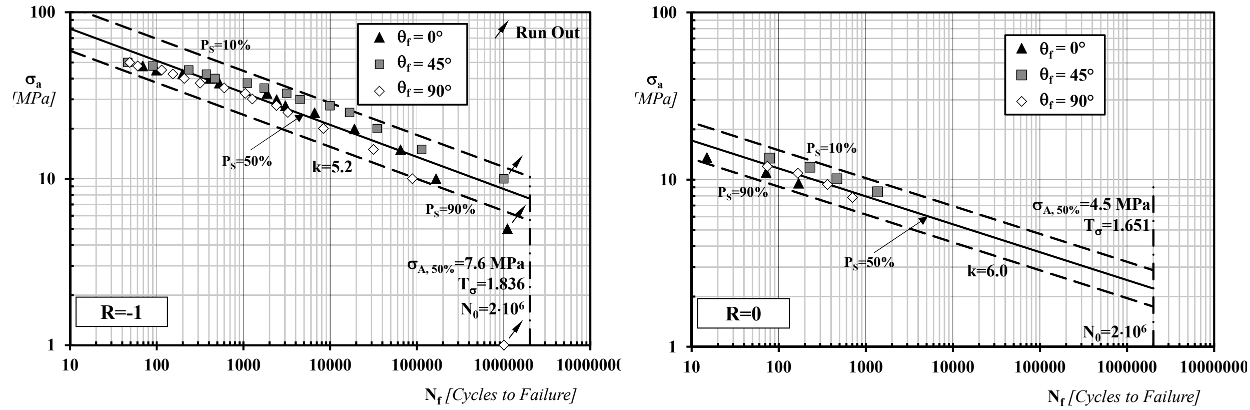


Fig. 1. Definition of raster angle θ_f.

Letcher and Waytashek (2014) investigated the axial fatigue behavior, under $R=\sigma_{min}/\sigma_{max}=-1$, of samples of 3D-printed PLA fabricated using commercial printer MakerBot Replicator 2x. Similarly, Afrose et al. (2016) tested, under R=0, a number of specimens manufactured using 3D-printer Cube-2, with these samples having width equal to 10 mm and thickness to 4 mm. In these two experimental investigations, the specimens being tested were manufactured flat on the build-plate by setting the infill level equal to 100% and the raster angle, θ_f (Fig. 1), equal to 0°, 45° and 90°.

The results generated by Letcher and Waytashek (2014) are summarized in the S-N diagram of Figure 2a, whereas those generated by Afrose et al. (2016) in the S-N chart of Figure 2b. The scatter bands reported in these two log-log diagrams – that plot the amplitude of the stress, σ_a, against the number of cycles to failure, N_f – were determined, for a probability of survival, P_S, equal to 90% and 10%, under the hypothesis of a log-normal distribution of the number of cycles to failure for each stress level, with the confidence level being set equal to 95% (Al Zamzami, Susmel 2017).



(a) (b)

Fig. 2. Scatter band determined by post-processing the experimental results generated by Letcher and Waytashek (2014) (a) and by Afrose et al. (2016) (b) by testing specimens of 3D-printed PLA with θ_f equal to 0°, 45° and 90°.

The charts of Figure 2 make it evident that, strictly speaking, angle θ_f does affect the overall fatigue behavior of 3D-printed PLA, even if a clear trend is not evident. At the same time, it can be observed that the relatively low values calculated for the scatter ratio, T_σ, of the endurance limit, σ_A, for P_S equal to 90% and 10% strongly support the idea that, from a fatigue design point of view, the effect of manufacturing angle θ_f can be neglected without much loss of accuracy. As to the values obtained for ratio T_σ, it is worth recalling here that, for instance, in the field of fatigue of steel welded joints, the available standard codes suggest, as recommended by Haibach (1992), using a reference value for T_σ equal to 1.5. Therefore, the T_σ values reported in Figure 2 confirm that 3D-printed PLA can effectively be designed against fatigue by simply treating this material as homogenous and isotropic, i.e., by disregarding the effect of the raster direction.

To conclude, it is worth observing that, in a way, this result is not at all surprising. In fact, similar to what is observed under fatigue loading, a number of very detailed experimental investigations (Ahmed, Susmel 2017a, 2017b, and 2018; Song et al. 2017) demonstrate that also under static loading the raster orientation has little effect on the overall strength of AM PLA.

3. Mean stress effect in fatigue of AM PLA

It is well known to structural designers that the presence of non-zero mean stresses can affect strongly the overall fatigue behavior of engineering materials and components. Therefore, having considered the effect of the raster direction, the next step in our investigation was studying the influence of superimposed static stresses, with this being done by running appropriate experiments.

Since, as highlighted in the previous section, from an engineering viewpoint the effect of angle θ_f can be disregarded without much loss of accuracy, we investigated the mean stress effect in fatigue of AM PLA by testing a large number of un-notched specimens of AM PLA that were all manufactured by setting θ_f equal to 45°. The dog-bone flat specimens (Fig. 3) we manufactured had net width equal to 6 mm and thickness to 3 mm and to 5 mm. Our samples were fabricated via FDM based 3D-printer Ultimaker 2 Extended+, by using, as parent material, white filaments of New Verbatim PLA with diameter equal to 2.85mm. The parameters for the AM process were set as follows: nozzle size equal to 0.4 mm, nozzle temperature to 240°C, build-plate temperature to 60°C, print speed to 30 mm/s, infill density to 100%, layer height to 0.1 mm, and shell thickness equal to 0.4 mm (i.e., equal to the diameter of the nozzle being used). As done by Letcher and Waytashek (2014) as well as by Afrose et al. (2016), all the specimens were fabricated flat on the build-plate.

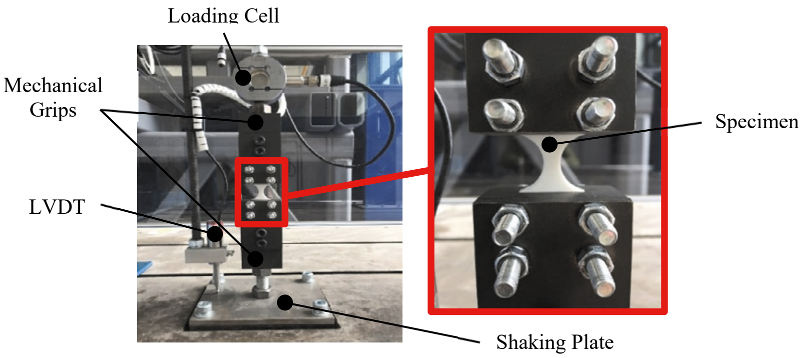


Fig. 3. Experimental set-up.

The fatigue results summarized in Figure 4 were generated by using a standard electric fatigue table that was modified and developed for these specific experimental trails (see Figure 3). In particular, the sinusoidal load histories being applied during testing were monitored via an axial loading cell, with the nominal cyclic displacement being measured using a linear LVDT. The adopted failure criterion was the complete breakage of the samples. The force-controlled experiments were run, at room temperature, under a load ratio, R, equal to -1, -0.5, 0, and 0.3. The nominal frequency was set equal to 10 Hz. Run out tests were stopped at $2{\cdot}10^6$ cycles.

The S-N charts reported in Figure 4 plot the results that we generated in the Structures Laboratory of the University of Sheffield in terms of amplitude of the applied stress, σ_a. As done for the data summarized in Figure 2, also our experimental results were post-processed, with a confidence level of 95%, by assuming a log-normal distribution of the number of cycles to failure for each stress level (Al Zamzami, Susmel 2017). The S-N diagrams of Figure 4 make it evident that, as expected, the strength of 3D-printed PLA decreases as the load ratio, R, increases. This implies that, similar to conventional engineering materials (and, in particular, similar to metallic materials), non-zero mean stresses lower the overall fatigue strength of AM PLA, with this being associated with a limited variation of the negative slope, k (i.e., in the range 7.5-8.9).

In order to better investigate the effect of non-zero mean stresses on the fatigue behavior of the tested AM PLA, the chart reported in Figure 5a plots the amplitude of the endurance limit vs. the corresponding mean stress, with both σ_A and σ_M being extrapolated at $2{\cdot}10^6$ cycles to failure. This diagram makes it evident that the presence of superimposed static stresses markedly reduces the fatigue strength of 3D-printed PLA. In particular, this reduction is seen to be more severe than the one which would be predicted by the classic linear formula due to Goodman, with this formula being commonly used to estimate the mean stress effect in fatigue of metals (Susmel 2009).

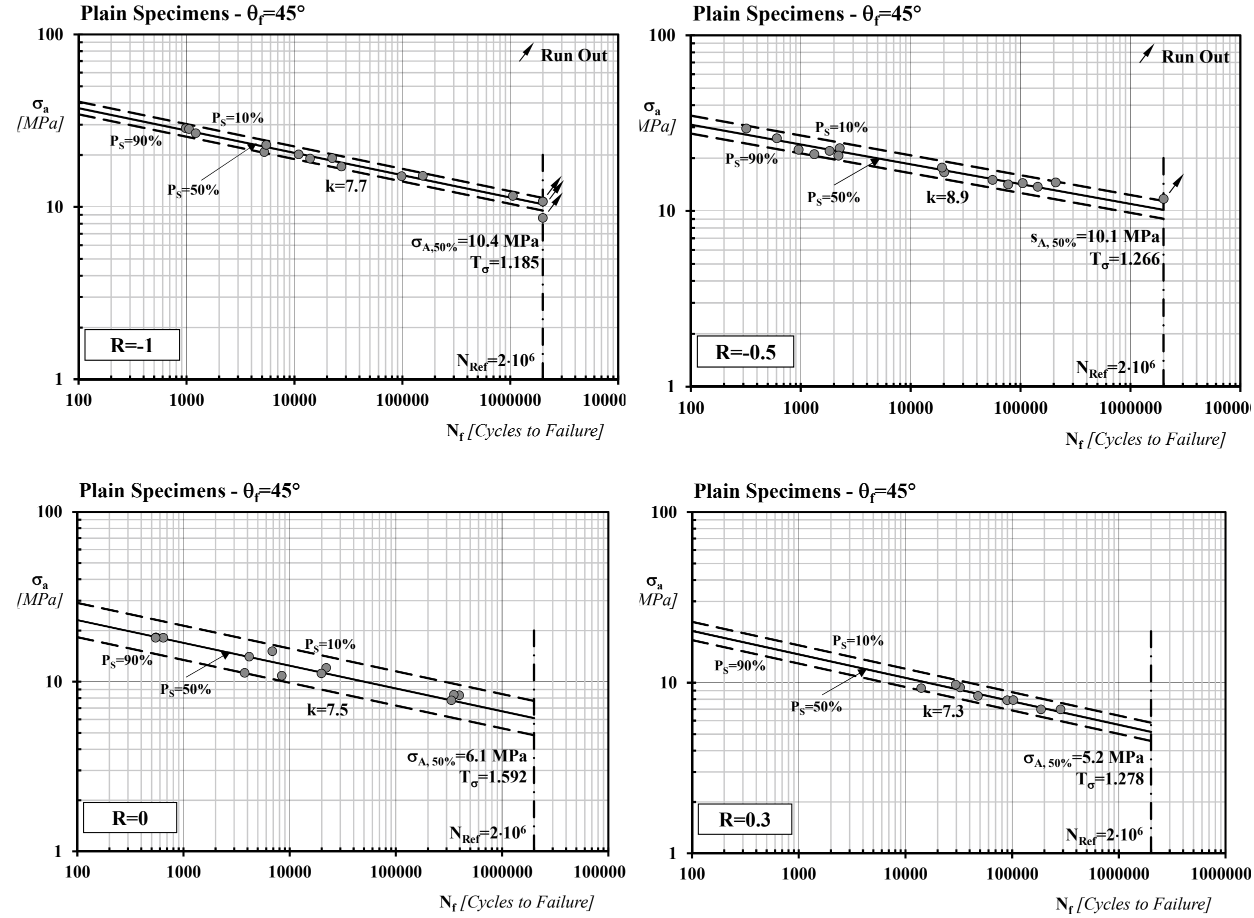


Fig. 4. Scatter bands determined by post-processing the experimental results we generated by testing specimens of 3D-printed PLA (Fig. 3) with θ_f=45° under a load ratio, R, equal to -1, -0.5, 0 and 0.3.

A different attempt to model the effect of non-zero mean stresses on the fatigue strength of AM PLA can be made by plotting the results summarized in Figure 4 in terms of maximum stress in the cycle, σ_{MAX}, extrapolated at $N_0=2\cdot10^6$ cycles to failure. It is interesting to point out here that a similar strategy was used successfully in the recent past to model the effect of superimposed static stresses on the fatigue behavior of un-reinforced concrete (Susmel 2014; Jadallah et al. 2016). The idea behind this assumption is that σ_{max} can be used - for certain specific materials - to assess the effect of load ratios, R, larger than -1 simply because this stress quantity already contains the mean stress information, since, by definition, $\sigma_{max}=\sigma_m+\sigma_a$.

The σ_{MAX} vs. R diagram reported in Figure 5b confirms that the use of this simple approach to model the effect of non-zero mean stresses on the fatigue strength of AM PLA results in a very low level of scatter, with the experimental points falling all well within two standard deviations of the mean. The fact that the σ_{max} based approach is successful in modelling the mean stress effect in fatigue of AM PLA is ultimately confirmed by the S-N curve reported in Figure 5c: when plotted in terms of maximum stress in the cycle, the data we generated by testing our specimens under R=-1, -0.5, 0, and 0.3 fall all within a relatively narrow scatter band, i.e. a scatter band characterized by a T_σ ratio equal to 1.6. Accordingly, it is possible to conclude that, as far as 3D-printed PLA is concerned, the mean stress effect in fatigue can effectively be accounted for by simply performing the fatigue assessment in terms of σ_{max}.

4. Conclusions

Not only by generating new experimental results, but also by considering a large number of data that are available in the technical literature, the present paper investigates the effect of raster direction and non-zero mean stresses on the overall fatigue strength of AM PLA. According to the re-analyses being discussed in the previous sections, it is possible to come to the two key conclusions reported below.

- In terms of engineering design against fatigue, the effect of raster direction can be neglected without much loss of accuracy. Therefore, 3D-printed PLA manufactured by setting the in-fill level equal to 100% can be modelled as a homogenous and isotropic material, with this resulting in a great simplification of the fatigue assessment problem.
- The effect of non-zero mean stresses on the overall fatigue strength of 3D-printed PLA can be modelled effectively by simply using the maximum stress in the cycle, σ_{max}.

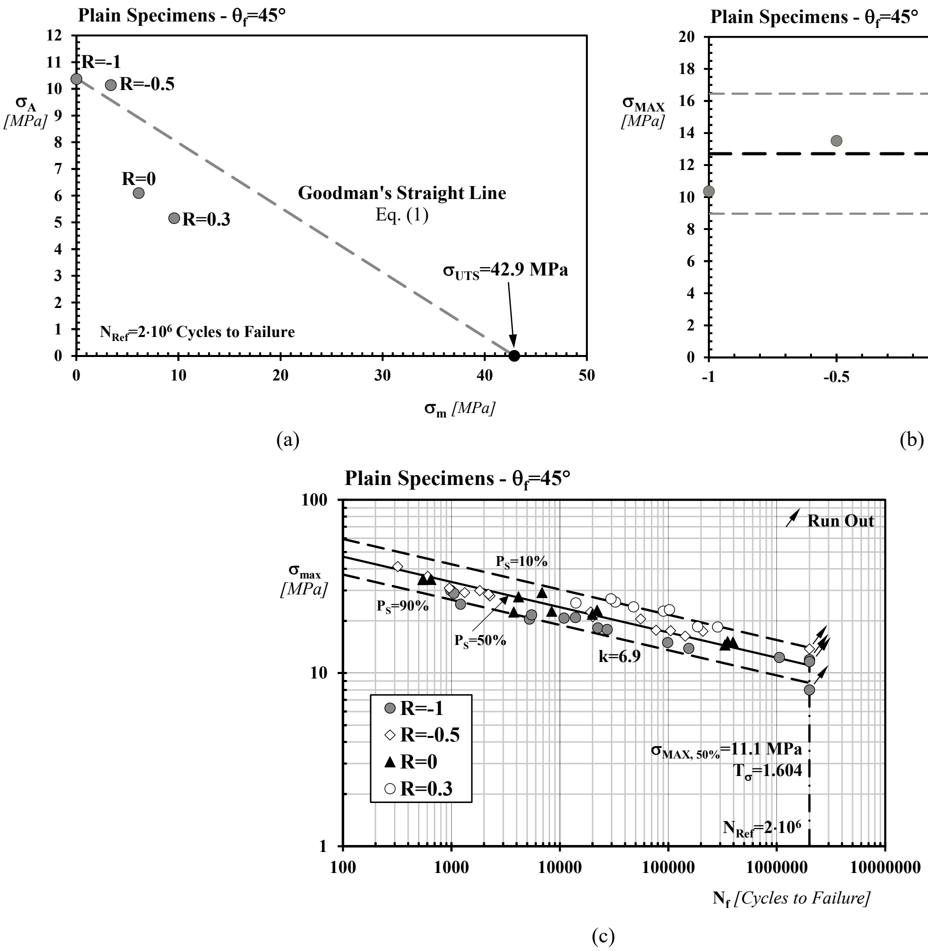


Fig. 5. Amplitude of the endurance limit, σ_A, vs. the corresponding mean stress, σ_M (a); relationship between endurance limit determined in terms of maximum stress, σ_{MAX}, and load ratio, R, obtained by post-processing the results summarized in Figure 4 (b); fatigue scatter band in terms of σ_{max} determined by re-analyzing together the data we generated under R=-1, -0.5, 0, and 0.3 (c).

References

Afrose F., Masood, S.H., Iovenitti P., Nikzad, M., Sbarski, I., 2016. Effects of part build orientations on fatigue behaviour of FDM-processed PLA material. Prog. Addit. Manuf. 1, 21-28.

Ahmed, A.A., Susmel, L., 2017a. Additively Manufactured PLA under static loading: strength/cracking behavior vs. deposition angle. Procedia Structural Integrity 3, 498–507.

Ahmed, A.A., Susmel, L., 2017b. On the use of length scale parameters to assess the static strength of notched 3D-printed PLA. Frattura ed Integrità Strutturale 11(41), 252-259.

Ahmed, A.A., Susmel, L, 2018. A material length scale based methodology to assess static strength of notched additively manufactured polylactide (PLA). Fatigue Fract Eng Mater Struct. 2018;1–28. https://doi.org/10.1111/ffe.12746.

Al Zamzami, I., Susmel, L., 2017. On the accuracy of nominal, structural, and local stress based approaches in designing aluminium welded joints against fatigue. Int. J. Fatigue 101, 137-158.

Haibach, E. Service Fatigue-Strength – Methods and data for structural analysis. Düsseldorf, VDI, 1992.

Jadallah, O., Bagni, C., Askes, H., Susmel, L., 2016. Microstructural length scale parameters to model the high-cycle fatigue behaviour of notched plain concrete. Int. J. Fatigue 82, 708-720.

Letcher, T., Waytashek, M., 2014. Material property testing of 3D-printed specimen in PLA on an entry-level 3D-printer. In: Proceedings of the ASME 2014 International Mechanical Engineering Congress & Exposition (IMECE2014), 14-20 November 2014, Montreal, Quebec, Canada, IMECE2014-39379.

Song, Y., Li, Y., Song, W., Yee, K., Lee, K.-Y., Tagarielli, V.L., 2017. Measurements of the mechanical response of unidirectional 3D-printed PLA. Mater. Des. 123, 154-164.

Susmel, L., 2009. Multiaxial Notch Fatigue: from nominal to local stress-strain quantities. Woodhead-CRC-Elsevier, Cambridge, UK.

Susmel, L., 2014. A unifying methodology to design un-notched plain and short-fibre/particle reinforced concretes against fatigue. Int. J. Fatigue 61, 226–243.