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Compressive behaviour of aluminium rectangular hollow tube using Digital Image Correlation (DIC) method

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Abstract. The lightweight structural application is commonly used aluminium material, which generally applied in automotive, military, aerospace and naval applications. The rectangular cross-section hollow tube of aluminium material performs the better compressive properties compared to other cross-section shapes. In order to investigate the compressive behaviour of aluminium tube, Digital Image Correlation (DIC) method is used to study the evolution of deformation and strain value. The quasi-static compressive test was performed, and the experimental result was compared with the DIC measurement results. It was obtained that the failure behaviour of the aluminium rectangular hollow tube was buckling mode with several inwards and outwards deformation. In addition, it was concluded that the DIC method results were lower than the experimental values on the maximum compressive stress and compressive modulus, which was considered as a good agreement between this two methods with 1.7 % percentage of error. It is suggested that DIC method is a sufficient method to measure the deformation and strain values with non-contact and non-destructive features.

1. Introduction

Nowadays, aluminium alloys have popularly been used in the automotive engineering applications due to its light-weight, corrosion resistance, recyclability and formability. Aluminium materials are largely used in light and crashworthy structural application compared to other metal materials such as aircraft, spacecraft and naval ship [1]. For instance, the aluminium crash box is commonly used to protect passengers and vehicle components by absorbing initial kinetic energy in the crash evidence [2]. Numerous works have studied to determine the cross-section shape of the crash box with aluminium alloys in automotive applications [3-7]. The rectangular cross-section of aluminium tube showed better compressive performance under quasi-static loading condition [8]. Therefore, the compressive behaviour of the rectangular cross-section aluminium tubes have been concerned and study by numerical researchers [9, 10].

Digital Image Correlation (DIC) is an innovative non-contact and non-destructive method to measure strain and displacement of crack propagation and material deformation [11]. In DIC method, a single illumination source and a single CCD (charged coupled device) are prepared to measure the specimen with the in-plane deformation [12]. 2D DIC method is not appropriate to obtain the measurement results from curved surfaces with three-dimensional deformation. In order to advance its limitation, 3D DIC method is developed to measure the three-dimensional deformation measurements from planar or curved surfaces [13, 14]. DIC technique is widely used in materials and engineering fields, which applies to measure the displacement and strain regarding as the structural analysis, finite element verification and quality assessment [15, 16]. Furthermore, several studies have been investigated the material properties using the DIC method [17-19]. This method could minimize the error of finite element simulation compared to experimental data, which is used to identify the material properties under quasi-static loading condition at high rates of strain [20].

Although there are several studies on the mechanical properties of aluminium material using DIC method, it is still limited works to investigate the compressive properties of aluminium material with a rectangular hollow tubular structure. Therefore, the aim of this paper is to deeply understand the compressive performance of aluminium tube with rectangular cross-section shape. The DIC method is used to measure the deformation evolution subjected to strain and stress values under compressive test. Experimental results and DIC results are analyzed and compared on compressive modulus and stress versus strain graph. In addition, the compressive behaviour of the aluminium tube is discussed as well.

2. Materials and Method

2.1. Specimen preparation

The tested specimen was selected aluminium 1100 type material with a rectangular hollow structure, and the dimension of aluminium rectangular hollow tube was as shown in figure 1. The parameter of the height to wall thickness ratio is 13.3. The properties of aluminium 1100 were mainly mentioned like tensile strength of 110 MPa, Poisson's ratio of 0.33 and an elongation of 12 %.

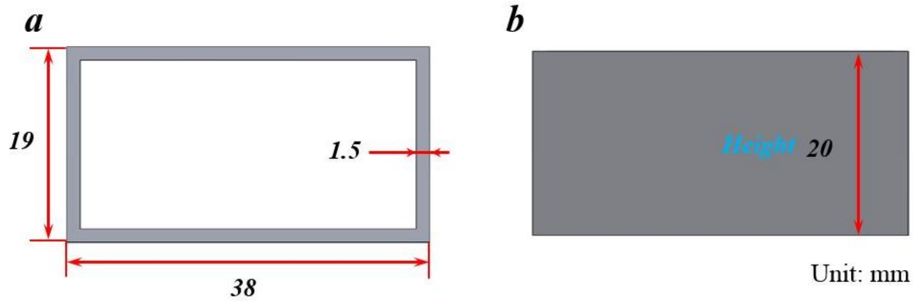

Figure 1. Dimension of aluminium rectangular hollow tube: (a) top view; (b) front view.

2.2. Quasi-static compression test

The quasi-static compressive test was performed using a standard universal testing machine Instron 3369 model with the maximum 50 kN load capability. The crosshead speed was set the 2 mm/minute. The load versus displacement curve was obtained by Bluehill software, and compressive behaviour of the tube was photographed during the test. The Nikon D3100 camera was used to recorded compressive behaviour images during the test, which was used to DIC method. However, the DIC software could only read the data from the movement of the random dots as on the surface of the tested specimen. Therefore, the aluminium rectangular tube was drawn the random dots using the black marker pen in a front surface of the specimen, which is shown in figure 2. In addition, in order to obtain better analysis results, the dots of the specimen should be cleared, and the recording zone must be accurate and adjusted.

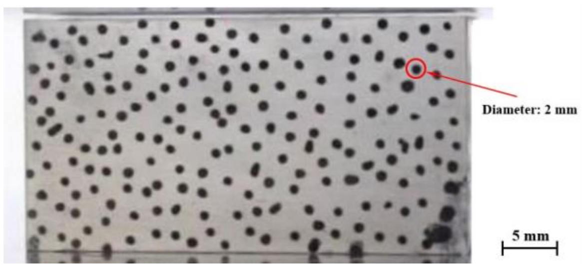

Figure 2. The front view of aluminium rectangular hollow tube with dots.

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2.3. Digital Image Correlation (DIC) method

The flowchart of Digital Image Correlation (DIC) method procedure is briefly shown in figure 3, which involved video record, format convert, running Ncoor program from Matlab R2017a, strain method of Ncorr program, the setting of DIC parameters, DIC processing, calibration and scale. The testing video was recorded at different levels of quasi-static loading, and strains obtained in the region using DIC method. The accuracy of strain value and spatial resolution could be improved through increasing the resolution of target specimen area [21]. In this study, it is used the Nikon D3100 camera with a resolution of 4,608 3,702 pixels (14.2 megapixels). The recorded video was converted to digital images using free video to image converter software and saved into the new file folder. The value of frame per second (FPS) is calculated, and the total converted images are divided by the duration of the video time as the second unit.

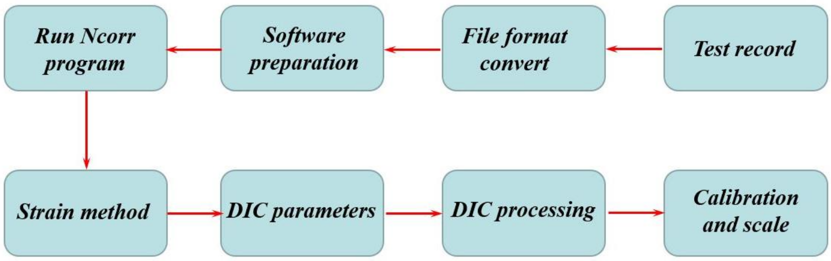

Figure 3. Flowchart of Digital Image Correlation (DIC) method procedure.

The Ncorr platform 1.1.2 version and Matlab R2016 version are downloaded and installed, which were the two software used in this study. Then, it is an important stage to determine and set the strain field obtained from the digital images. The Ncorr platform is suggested to use the toolboxes required such as Image Processing Toolbox and Statistics Toolbox [22]. In addition, it is also required to post-processing and correlation method. The procedure of image settings is used to correlate and process for displacement/strain field of tested specimen. The relevant images as the reference image were loaded when previous software is successfully setup. The current images were loaded based on the entire load used in this test, and the setting of the reference image is shown in figure 4.

Figure 4. Loading of the reference and current images.

The reference image refers to the initial image recorded of the tested specimen before the compressive deformation occurred. The current image is used all the subsequent imaged to be correlated, which are compiled and ready to be processed via the correlation algorithm. The region of the specimen was drawn according to the area of the determined strain filed, and it was mainly depended on loading condition, failure behaviour and deformation mode. In this study, aluminium rectangular hollow tube was deformed in the middle of the total height, as shown in figure 5.

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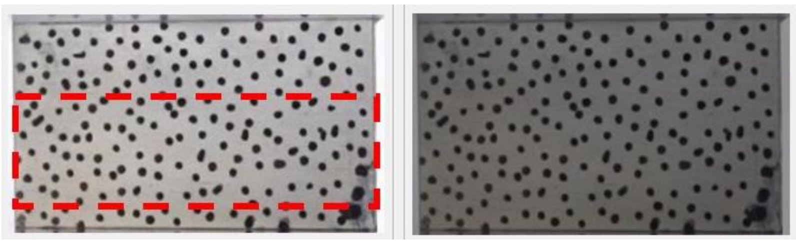
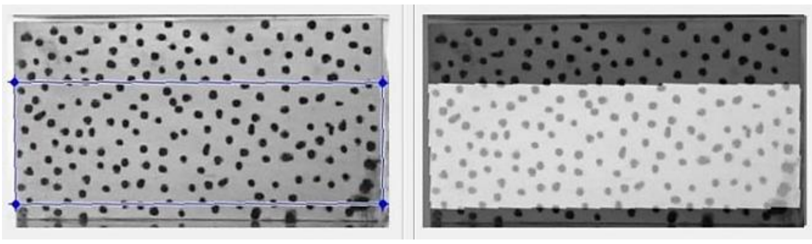


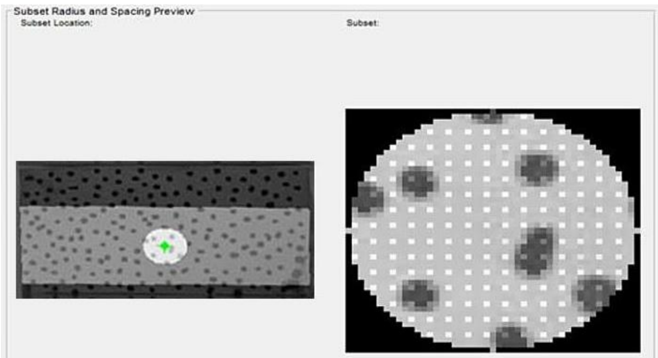
(a)



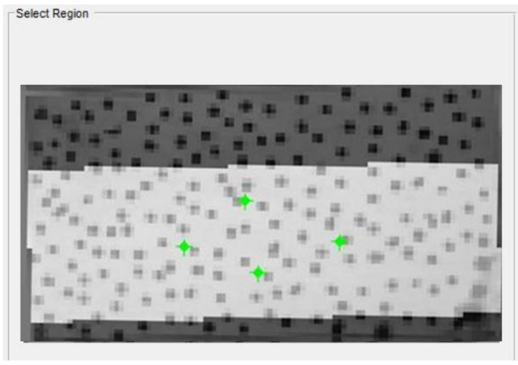
(b)

Figure 5. Setting of DIC parameters: (a) selecting the region of the tested specimen; (b) region selected condition.

Several parameters were provided on the left box on the software interface, and a green point was placed in the “Subset Location”. For the subset option, the size of the subsets was dependent on spacing between the linked dots, which is used to reduce the computational load. Multithreading options are used for the speed up the computation process. The larger the number of threads, the more precise the results could obtain [23]. The parameter setting of the subset option is shown in figure 6, which involves the region interest and seed set in the region area. The seed region process provided the initial condition of the DIC method process, and the seed placement process was completed, as shown in figure 6(a). For instance, the single region was processed when it was set in the ROI interface as shown in figure 6(b).



(a)



(b)

Figure 6. Subset option setting of DIC parameters: (a) subset option and region interest; (b) setting seed on region condition.

The seed region was checked to avoid its incorrect process, which showed the initial region for DIC method. For calibration and scale process, it was used to specify the corresponding pixels with the unit measurement according to its dimension. It converted the displacement from pixels to the true unit. The real value of the width from the tested specimen can insert at the “# of units”, which was 38 mm in this case study. The relevant setting of calibration and scale is briefly presented in figure 7.

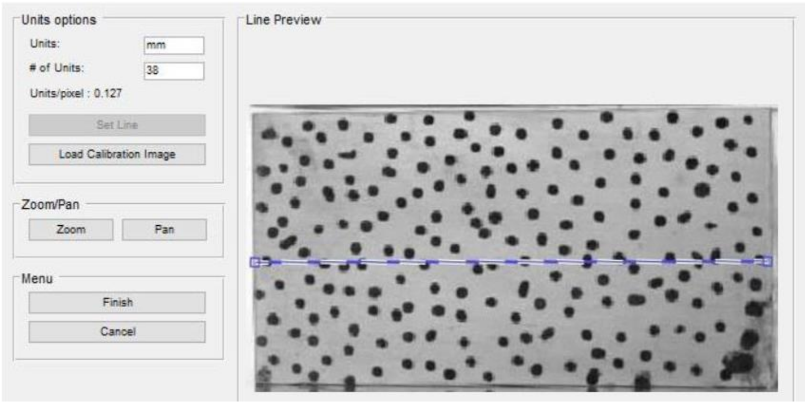


Figure 7. Calibration and scale process of record image using DIC method.

3. Results and discussion

3.1. Result of experimental test

Figure 8 showed the compressive behaviour of the aluminium rectangular hollow tube under the quasi-static compressive loading. It was observed that buckling mode occurred around the middle region of the aluminium rectangular tube. Therefore, the buckling mode was the main failure behaviour in the plastic deformation stage under quasi-static compressive loading, which agreed with similar studies on compressive properties of aluminium rectangular tube by other researchers [24-26]. Furthermore, the damaged specimen was illustrated in figure 9, which presented failure behaviour with buckling mode. There were some inwards and outwards deformation occurred on the boundary condition, which due to friction between the tube wall and crosshead.

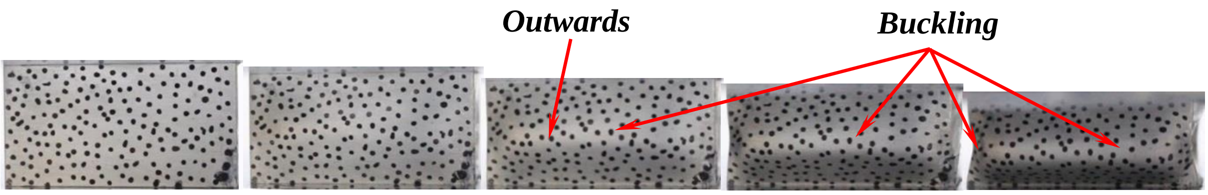
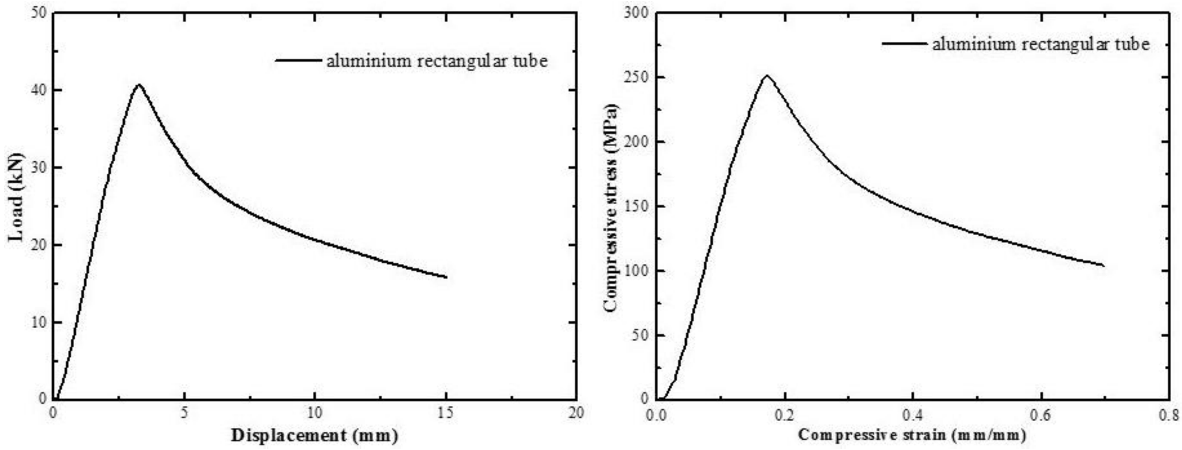


Figure 8. Compressive behaviour history of the aluminium rectangular tube under quasi-static compression test.

Figure 9. The damaged the aluminium rectangular tube.

The compressive properties of aluminium rectangular tube were investigated under the quasi-static loading condition, as shown in figure 10. The load markedly increased until it reached the maximum load of 40.74 kN in the elastic deformation stage. The load was slightly decreased during the plastic deformation stage, which mainly occurred the buckling mode in this stage. It was found that the maximum compressive stress occurred at the maximum load point of 245.48 MPa.



(a) (b)

Figure 10. The experimental traces of the aluminium rectangular hollow tube: (a) load versus displacement trace; (b) stress versus strain trace.

3.2. Result of Digital Image Correlation (DIC) method

Two methods are used to study the compressive properties of aluminium rectangular hollow tube. The stress versus strain graph is calculated according to its load versus displacement graph. The stress versus strain graph of DIC method is obtained from the DIC Ncorr software. There were three main conditions using DIC method, which were before compression, applied compression load and buckling at the middle of the specimen. Figure 11 presented the contour plot of measured strain before the load applied, which involved several parameters such as analysis type, image correspondences and correlation coefficient value. It obtained strain values with a negative value or 10-4 unit, which was recorded as an initial strain value before the load applied. Furthermore, the red contour plot is the area when the compression machine started to apply the load on the specimen. The maximum strain value in the area (red colour) with 0.052 and the minimum strain value (blue colour) is -0.173.

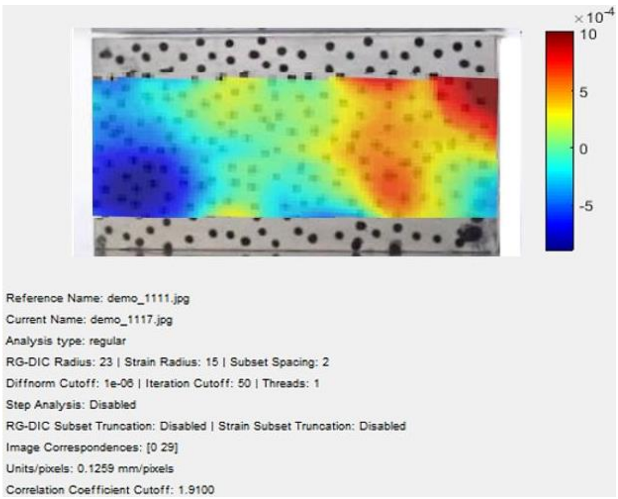


Figure 11. The result of DIC method before the load applied.

Figure 12 exhibited the contour plot of measure strain when the load applied, and it was observed the concentrated red colour around the middle of the specimen. It was shown that the strain region developed under the load applied, which indicated the deformation of buckling mode. Figure 13 showed the contour plot of strain value when buckling mode deformation initially occurred in the middle of the specimen. The reading of strain value was starting to become red colour around the

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middle region of the specimen, as shown in figure 13. Each of the strain value could slowly change its measurable values until the compressive test is done. The reading of strain and stress values are completely measured and obtained at the selected point.

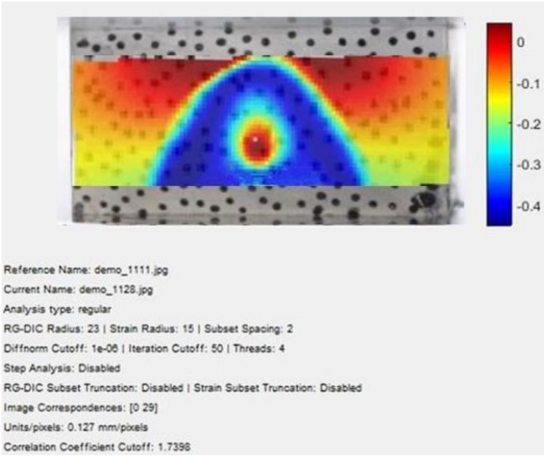

Figure 12. The result of DIC method when the load applies.

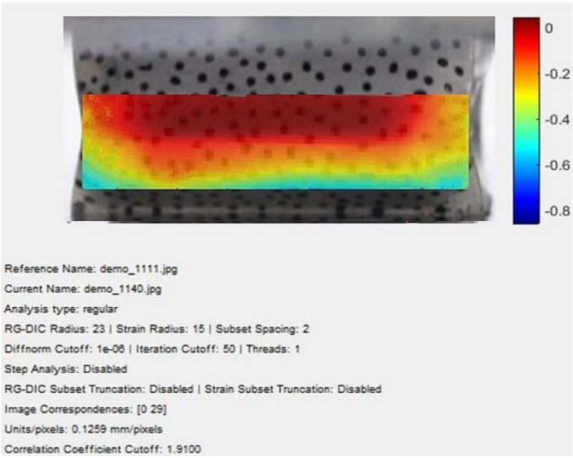

Figure 13. The result of DIC method when the buckling mode in the middle of the specimen.

The experimental data and DIC method data were compared and analyzed, which exhibited a similar trend pattern, as shown in figure 14. In order to obtain the compressive modulus value of this aluminium rectangular hollow tube, the data was only analyzed under the elastic deformation stage. For this case, the DIC method cannot detect the full pattern of the specimen due to the different value ranges between strain and stress. The maximum of stress value was 245.48 MPa for experimental method result and 241.12 MPa for DIC method result. The experimental result was a little bit higher than the result of DIC method, which provided the 1.7 % percentage of error. It was considered as a good agreement between experimental and DIC results. The compressive modulus was calculated according to stress versus strain trace, which obtained 1.22 GPa for the experimental case and 1.19 GPa for DIC case.

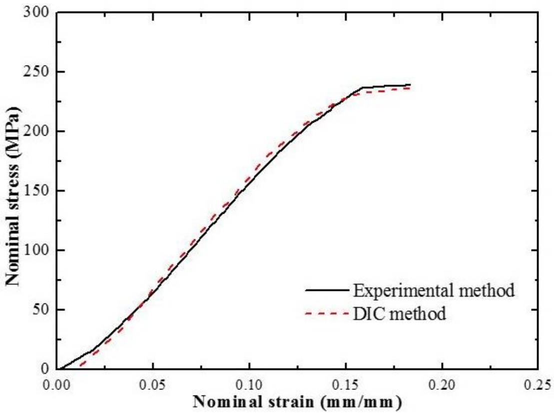

Figure 14. Results of the stress versus strain trace between experimental and DIC methods.

There are several factors that affect the results from the DIC method, which refer to the type of the material used, structural pattern of the tested specimen, size of the dots and the quality of video recorded [14, 27]. For the used material, it affects the range of error ratio with the provision of material type. For structural pattern, the suitability of the tested structure is another important parameter, which is due to the DIC software could only detect in the X and Y-axis. Therefore, the tested structure should select a two-dimension shape to analyze the strain value using DIC method.

For the size of the dots, it provides a high impact in order to obtain accurate results. The dots should follow the actual size, which affects the tracking procedure. The relevant displacement will be lost as the size dot is larger than the subset size, and it causes the dot cannot be recognized in the searching zone. Therefore, the dot should be smaller as the size of the subset and located in the search zone [28, 29]. Furthermore, it is also highlighted that the higher resolution image can generate better results by providing good lighting and closed distance between camera and specimen. The DIC software can only read the data from the movement of the dots on the surface of the specimen.

4. Conclusion

In recent years, Digital Image Correlation (DIC) method attracts much attention compared to other methods, which is generally used to measure the displacement mapping with cost-effective purpose. In this study, the compressive behaviour of aluminium rectangular hollow tube was studied, which mainly occurred the buckling mode of failure deformation. The load versus displacement and stress versus strain graphs were discussed. For DIC method, the contour plots of measured strain were summarized and highlighted on three conditions, which were before the load applied, applied load and buckling mode condition in the middle of the specimen. Furthermore, it was concluded the reasonably good agreement between the experimental test and DIC method, which obtained 1.7 % percentage of error. The experimental results were a little bit higher than the measurement values of DIC method. In addition, several factors affected the accuracy of DIC measurement results were discussed, which involved material type, specimen structural pattern, size of the dots and the quality of video recorded.

Acknowledgments

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