Clustering-Based Post-Processing of Experimental Data for Double Glass Units

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Abstract. Double glass units (DGUs) consist of glass plates separated by a gas-filled cavity sealed by perimeter spacers. The glass plates resist to applied loads, whereas the enclosed gas mainly contributes to thermal and acoustic insulation in buildings or other structures. Load transfer between the plates occurs through a load-sharing mechanism that is difficult to be quantified, particularly regarding its influence on vertical deflections of the glass. Although this phenomenon has been recently investigated experimentally, a major challenge of laboratory testing is the post-processing of large outputs. To address this issue, this study employs the k-means clustering algorithm as a data-driven tool for experimental data analysis. The objective is to identify optimal clusters that provide accurate approximations and enable direct relationships between elastic stiffness and deflections. The results show that k-means clustering produces reliable stochastic approximations, allowing the generation of deflection maps for both the upper and lower glass plates. Compared with traditional manual or analytical post-processing methods, the proposed approach offers an efficient and robust alternative for estimating stiffness values and glass deflections.

Keywords: k-means; DGU; mechanical deflections; structural analysis.

1 Introduction

With the progressive development and widespread adoption of the artificial intelligence, numerous algorithms have been employed to model input-output relationships with high precision. This approach significantly reduces human workload and enhances the efficiency of data processing and analysis.

The k-means algorithm is used for processing several parameters and it appears particularly effective for analysing datasets with multiple variables and dimensions [12]. It becomes especially valuable when dealing with "big data" issue, where conventional methods often fall short. As noted in [10] the greater the number of predictor variables, the harder it is to interpret and isolate each predictor variable effect; also, clustering analysis can help identify data patterns, merge similar components, and prepare the groundwork for predictive model construction. Due to its simplicity, efficiency, and versatility, the k-means algorithm has been widely applied across various disciplines beyond structural and mechanical engineering.

Therefore, this approach has provided the foundational inspiration for the present work in developing the k-means algorithm also for double glass units (DGUs), which are insulating glass composed by glass plates entrapping a cavity filled with air sealed by perimeter metallic spacers usually made in aluminium or steel. The structural function of the glass plates is to withstand the external actions, whereas the role of the gas is correlated to the insulation of heat and noise in buildings, trains, ships, etc. [14]

Figure 1 shows a real photo of buildings made by insulating glasses [8]. This photo helps to illustrate not only the architectural beauty but also the utility and sustainability of the proper use of insulating glass in line with “building resilient infrastructure” in accordance with the 2030 Agenda for Sustainable Development [2].

Fig. 1. University of Toledo Engineering Building Toledo, Ohio, USA (retrieved from [8]).

The transmission of the external loadings between the glass plates, through the gas and spacers, is called “load sharing” phenomenon. In literature many studies show limited structural analysis in particular regarding this phenomenon, which in more advanced models has been better studied to estimate the out-of-plane deflections of the glass plates [4]. Other studies analyse this phenomenon also accounting for the buckling and the performance of the laminated DGUs [14, 15].

The best model that considers well this phenomenon is the Betti’s analytical method (BAM), which has been validated experimentally in [3]. In [13], it is stated that the BAM is a “promising procedure that allows consideration of a wider range of geometries and loading configurations” and it is “an approach may be added in the final version of the Eurocode”.

In this paper, the k-means algorithm has been used to find a direct method to "clean" the results of mechanical laboratory tests, which are usually raw outputs that they must be treated in analytical or visual way by filtering several data. In this sense, the paper is about post-processing laboratory measurements of deformed glass with greater accuracy than manual approaches. Here the out-of-plane deflections and elastic stiffnesses of the IGU glasses supported on four sides under linear and concentrated loads have been analysed. The results have been compared to that validated in [3].

The primary objectives of the k-means algorithm are: (i) to create clusters of cases or variables with high internal similarity and low similarity between groups; and (ii) to reduce data complexity in order to derive meaningful and actionable insights. In this sense, this algorithm can be very useful to treat in a more direct and quick way the outputs from experimental laboratory tests. To the best of the authors' knowledge there are no studies where the k-means algorithm has been used for this purpose for DGUs.

2 Materials and Methods

2.1 Collected data

From previous published studies by the authors regarding the mechanical analyses of DGUs [3, 4] it was possible to collect several experimental data to be used for the present paper. In this sense, previous studies are used here as references to provide a new method for processing results from laboratory tests.

In [3, 4], the BAM model inserted in the new Eurocode [5] has been validated hence they can be considered as valid results. In particular, the collected data regard vertical deflections of DGUs under concentrated and linear loadings.

Figure 2 shows an example of the mechanical test of a DGU indicating the wooden box, which has been built to simulate the mechanical supports, the hydraulic dynamic actuator and load cell to produce and control the external load, and the metal bar to transfer the load in a linear way to the DGU. For a concentrated load a small wooden plate was used instead of the bar.

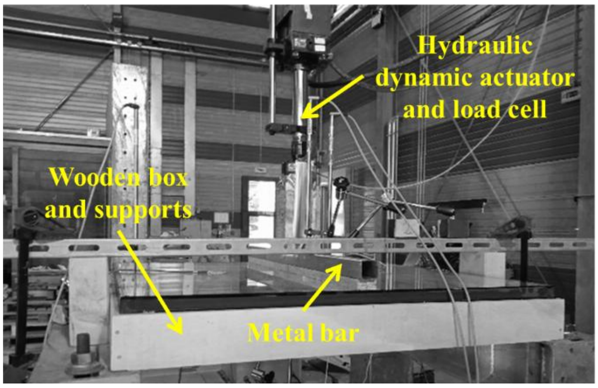


Fig. 2. Photo of the mechanical test of a DGU.

All studied DGUs are supported on 4 sides and are subjected to concentrated (about 1.0 kN) and linear (about 2.0 kN) loads. These values were sufficient to estimate the load-displacement curves hence the elastic stiffness avoiding brittle cracks (for more details see [3]).

For the purpose of the present study, the values of interest are considered as “raw values”, which are treated here by the k-means algorithm to find possible correlation. These raw values, regarding the different DGUs (3 rectangular and 1 square), which are made by a superior and an inferior glass, aluminium spacers and air, are listed in Table 1.

Table 1. Used parameters for the analyses [3, 5].

Parameter	Value
Glass thickness	6.0 – 8.0 mm [a]
Gas cavity thickness (air)	12.0 – 18.0 mm [a]
Side length	0.50 – 2.0 m [a]
Young’s modulus of the glass and aluminium	70.0 GPa
Poisson ratio of the glass	0.22
Poisson ratio of the aluminium	0.30
Density of the glass	2500.0 kg/m^3
Density of the aluminium	2700.0 kg/m^3
Density of the gas	1.18 kg/m^3

[a] The dimensions of the rectangular (0.50×2.0 m) DGUs are: 8×18×8 mm, 8×12×8 mm, 6×18×6 mm; the dimensions of the square (1.0×1.0 m) DGU are: 8×18×8 mm.

The values in Table 1 follow classical manufacturing, however some differences are possible in different world markets. Note that in practical applications for commercial façade units and residential windows, sizes for glasses around 1800.0 × 900.0 mm and

1250.0 × 750.0 mm, respectively, can be usually found in China [6, 7]. However, due to the great demand of this type of structures and more complex and futuristic solutions other sizes can be also manufactured, as for instance, 500.0 × 2000.0 mm and 1000.0 × 1000.0 mm in Europe. However, the method proposed in this study can be valid for any size.

2.2 Methodology

The main goal of the k-mean algorithm is to produce groups with a high degree of similarity and to reduce the complexity of the data treatment. For brevity, here only the main procedures are explained since in general this methodology is well known.

Firstly, it is necessary to collect relatively homogeneous data as shown in previous section. This initial step allows to provide more reliable outputs. The used values in the present paper refer to similar DGUs in term of mechanical characteristics hence they can be correctly used for this algorithm.

Then, the values are plotted in pairs, since the k-means algorithm adopts the Cartesian coordinates, providing groups of points (or clusters). By choosing the distance between the centre of a cluster, c_i, and general points, p_{ij}, with $i = \{1, 2, 3, \ldots, k\}$ and $j = \{1, 2, 3, \ldots, n\}$, where k indicates the cluster numbers, the estimation of the Euclidean distance, E, and its minimum value can be obtained by, respectively:

$$E = \sum_i^k \sum_j^n \left\| p_{ij} - c_i \right\|^2 \tag{1}$$

$$\min\{E\} = \min\left\{\sum_i^k \sum_j^n \left\| p_{ij} - c_i \right\|^2\right\} \tag{2}$$

where the parameter n represents the number of cases included in a cluster k providing specific p_{ij} points (note that two subscripts are necessary since, as mentioned, the Cartesian coordinates in a plane are used).

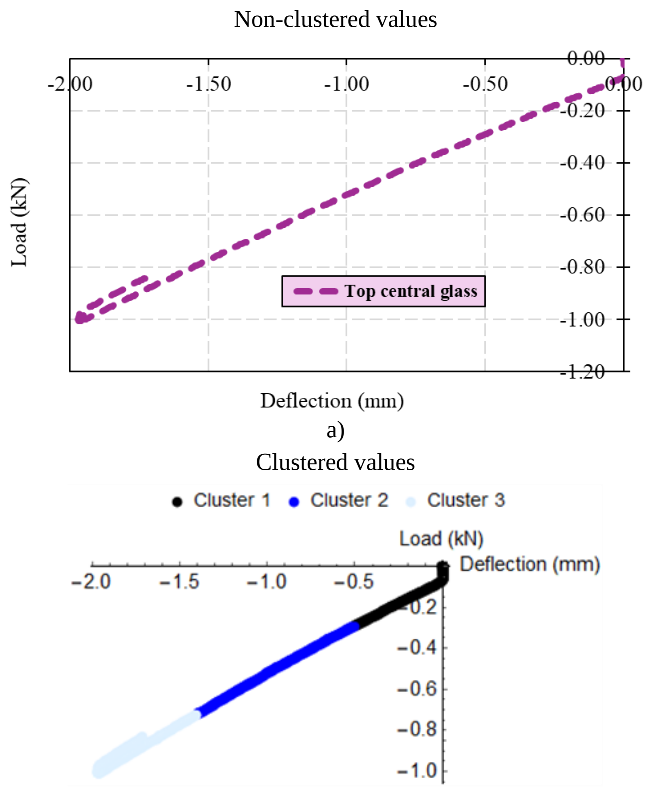
The position of c_i is defined in a random way and then is adjusted. Mathematica software [9] provides automatic solutions under multiple iterations that are intrinsically computed. This software considers that the elements with high E distance are low similarity. Finally, for each c_i value, the condition $dE/dc_i = 0$ must be verified.

In general, this algorithm is not difficult to be implemented also concerning the choosing of k-number. Here the value of k = 3.0 has been adopted since in previous studies (e.g., [10]) it has been noted that in general this number of clusters is sufficient to understand the phenomenon; this is because clusters 1 and 3 can serve as external limits thus cluster 2 can provide a reliable mean trend.

However, the analytical method to define the k-value consists in plotting dE values vs. k numbers and finding the “knee” of the obtained curve. The point where the curve changes its slope represents an optimum k value as explained in [1, 11]. In [1] the empirical effectiveness of this method has been demonstrated not only for choosing the number of clusters but also for identifying underlying structure, on a wide range of simulated and real-world data sets.

3 Analyses and Results

By applying the described method, the raw values obtained by experimental laboratory tests can be plotted by using three clusters. To show the effects in applying the k-means algorithm, in Fig. 3a) the out-of-plane deflections (or vertical deflections) of the glasses in function of the applied concentrated loadings are plotted by using non clustered values (i.e., raw values), whereas Fig. 3b) shows the clustered values highlighting three groups. The deflection-load curves refer to the top central rectangular DGU under concentrated load (for brevity only one example is shown).



b)

Fig. 3. Deflection values of the glass under concentrated load for a) non-clustered and b) clustered values.

In general, all non-clustered curves have some inconsistent parts, e.g., non-linear branches, the presence of discharge curves (like Fig. 3b)), curves that start at different times, etc.; hence these results could justify the use of the k-means algorithm to adjust and “clean” them. All tests provided a total of about 35.0×10^3 data, which must be treated to obtain useful outputs; in this sense, the use of the k-means algorithm can be beneficial for the purpose of the present study.

The manual adjustments have been made in terms of i) signs, where bottom and top deflections are considered positive if directed downward; ii) axis origins, where the deflections are null when the load is null; and time phases, where the deflections and load start at the same time; and iii) the unloading curves, from the maximum load to zero, have been deleted. Therefore, the results under these adjustments provide the validated values published in [3] and called in the present paper as “exact” values. Thus, they are compared with the clustered values obtained by Eqs. (1)-(2) in this analysis to appreciate the efficiency and goodness.

Figure 4 shows some comparisons in terms of probability density function (PDF) curves with respect the elastic stiffness (i.e., load/displacement ratio) for some DGUs under linear and concentrated loads. The k-means algorithm considers a cluster as a probability for each case, based on the mean value, μ_i, standard deviation, $\pm\sigma_i$, and its PDF; for this reason, this type of representation is consistent in this way.

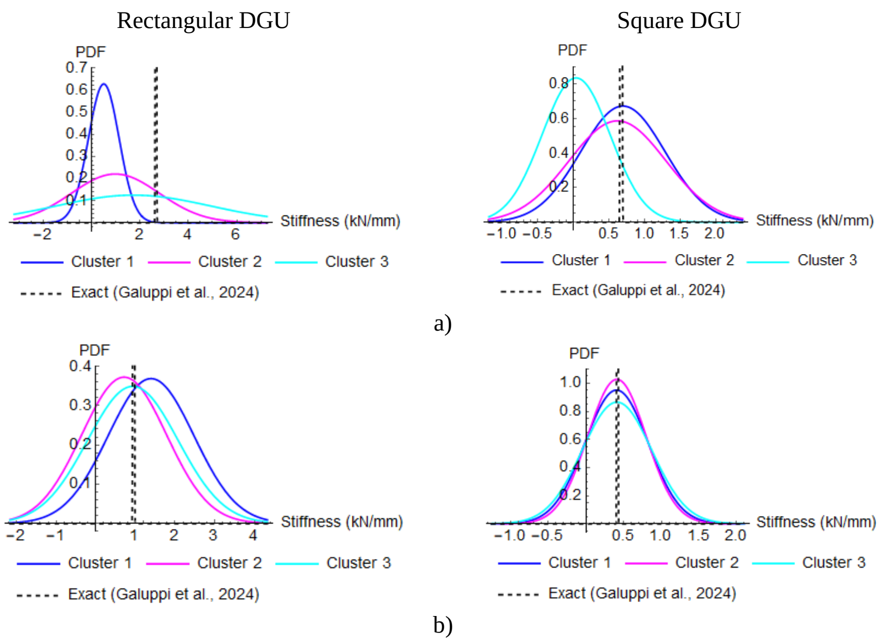


Fig. 4. PDF curves in function of the stiffness of the superior glass for a) linear and b) concentrated loads (some results).

Results for three clusters are shown and compared with the mentioned exact results; in this sense 48 stochastic analyses have been generated. The exact stiffness follows a linear-elastic behaviour, whereas the stiffness by cluster analyses could include some non-linear phenomena; however, the use of this algorithm also serves to find in a direct way the possible elastic stiffness at any point of a DGU.

The cluster that provides a μ_i value more similar to the exact value is assumed as the best cluster. Some clusters have a sharpened shape with a low $\pm\sigma_i$ value (i.e., low statistical error), however they could be not a better solution. In general, the deflections measured at the superior glass under concentrated load appear less scattered, with respect linear load, probably due to a direct and immediate transmission of the concentrated load up to the measuring point. In fact, the linear load can create strong stress concentrations in an extended part of the glass altering this transmission. Actually, in [3], the best agreement has been noted for superior deflections under concentrated load.

Some differences have been also registered between superior and inferior deflections of the glasses. In an DGU the transmission of the load between both glasses can be altered with different "velocity" due to influences of the mechanical properties of the internal gas and metal spacer. In a representation like Fig. 4 it is difficult to quantify separately the influence of the gas and/or spacers, as well as the geometric effects, since this algorithm follows a process purely geometric; however, both effects play an important role thus they must be considered. In general, the best results are provided by cluster 2 with a mean value of 1.01 ± 0.06.

Figure 5 shows all results of the exact solution (y-axis) with respect the approximated solutions (x-axis) obtained in this study regarding the stiffness of the DGUs. The correlation appears satisfactory with a R-squared value, R^2, of 0.97 – 0.99, showing the goodness of the algorithm, hence it appears a base for possible estimations for new and future DGUs. The loads have been divided due to their different influence on the DGUs, hence in Fig. 5a) the curves refer to the concentrated loads, whereas Fig. 5b) to the linear loads. This allows to obtain some trend lines and relations more useful to estimate a possible stiffness for DGUs.

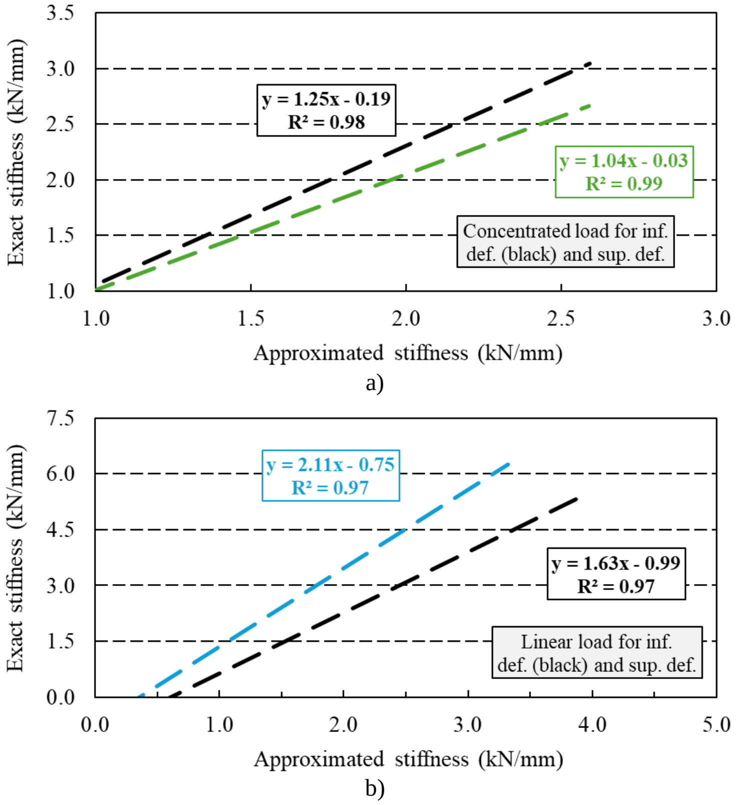


Fig. 5. Relation between exact and approximated stiffness for a) concentrated and b) linear load.

By using four relations in Fig. 5, it is possible to estimate the out-of-plane deflections of the glasses. These relations should represent the innovative and interesting aspect of this methodology. Note that the relations calculate the stiffness which, being linear elastic, is direct correlated to the deflection. The estimated relations are valid only for positive values (i.e., $y \geq 0$) to respect the physical meaning of the mechanical model.

Finally, Fig. 6 shows the mapping of the superior/inferior and central/later deflection points for some DGUs. Figure 6a) refers to a rectangular DGU, whereas Fig. 6b) to a square DGU. The exact values are indicated in black since they are calculated in previous studies and they are very similar to the clustered values obtained in this paper (mainly for cluster 2), whereas new values are shown in orange.

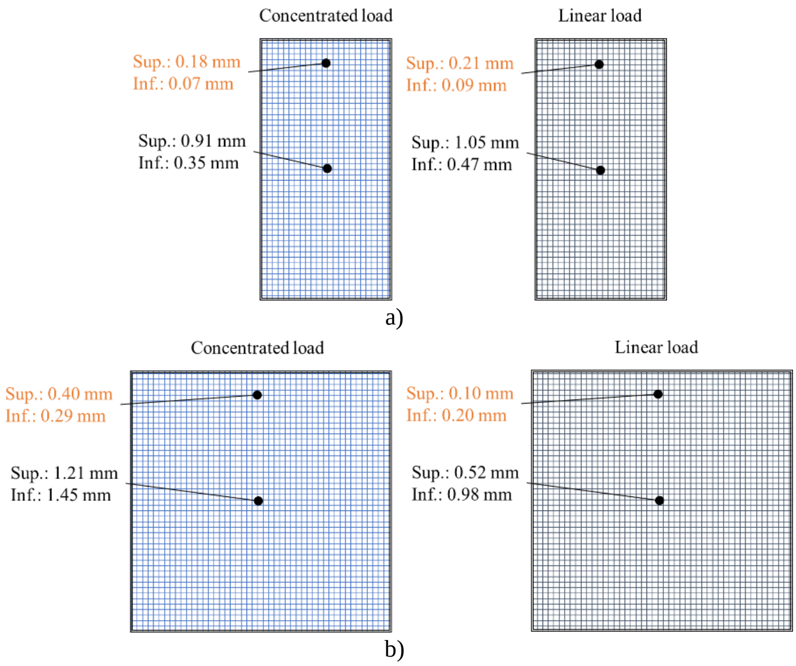


Fig. 6. Mapping of the deflections for a) rectangular and b) square DGUs (some examples).

The obtained values are very small; however, this approach is valid for any value under the linear-elastic model thus under the mechanical hypothesis of small deformations. In general, due to the brittle behaviour of the glass, small values are usually registered, and they represent the values of interest for design.

Results show that instead of using manual and analytical approaches to clean and adjust a-posteriori the mechanical laboratory tests, by using k-means algorithm and the estimated approximations it is possible to find good values for stiffness and out-of-plane deflections for a preliminary design.

4 Conclusions

In this paper the k-means algorithm applied for DGU glasses has been used to simplify the traditional mode to treat a-posteriori the results obtained from experimental laboratory tests. In particular here the out-of-plane vertical deflections thus elastic stiffnesses of square and rectangular DGUs were analysed. From mechanical tests, developed in previous studies, several data have been collected and treated by k-means algorithm. It appears that this approach is quick and quite reliable, however it is valid under specific hypotheses and conditions explained in this paper.

The k-means algorithm has been developed numerically by parametric software, obtaining about 50.0 statistical results. In general, cluster 2 appears the best cluster to be considered. Linear trend and relations for concentrated and linear loadings have been obtained to estimate a possible elastic stiffness for DGUs. Thus, a mapping of out-of-plane deflections of the superior and inferior glass has been plotted a-posteriori.

Instead of using manual and analytical approaches to clean and adjust the mechanical laboratory tests, by using k-means algorithm and estimated approximations it is possible to find good values for stiffness and deflections, which are the key parameters for designing glasses.

Acknowledgements

The authors acknowledge the Portuguese company SOSOARES and the ITECONS institute for prototyping the insulating glass units and carrying out the laboratory tests. The authors acknowledge the University of Salamanca (USAL), Spain, for providing a Wolfram Mathematica license and their institutions for covering the publication access fees, when applicable, required to download the referenced papers.

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