STRUCTURAL SIZING AND SHAPE OPTIMISATION OF A LOAD CELL

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Abstract

This paper presents a structural application of a sizing and shape based on a reliability-related multi-factor optimisation. The application to a load cell design confirmed that this method is highly effective and efficient in terms of sizing and shape optimisation. A simple model of the S-type load cell is modelled in finite element analysis software and the systematic optimisation method is applied. Structural responses and geometrical sensitivities are analysed by a FE method, and reliability performance is calculated by a reliability loading-case index (RLI). The evaluation indices of performances and loading cases are formulated, and an overall performance index is presented to quantitatively evaluate a design.

Index Terms: *Multifactor optimisation, Finite element analysis, Load cell*

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1. INTRODUCTION

Rapid advances in multi-objective and multi-disciplinary optimisation related to component designs as a tool in solving engineering design problems. Multi-objective optimisation that incorporates reliability assessment is presented [1]. This research addresses a design optimisation problem in which the load cell design is required to satisfy multiple criteria such as mechanical strength and stiffness, mass, and reliability feature under a single loading case.

Load cell is a device normally use in weighing industrial. The capacity of load cell is vary from 25 kg up to 20 tons. One of the most popular types of load cell is S-type load cell. It was originally designed for in-line applications to convert mechanical scale to digital by replacing the spring. A load cell is a transducer that converts a force into electrical signal. The force is sensed by a strain gauge that will be converted into electrical signals.

The main objective of this paper is to design an S-type load cell. Multi-objective and multi-disciplinary optimisation technique and reliability analyses is applied in order to minimise stress and displacement, mass, and to maximise the reliability index simultaneously.

2. OPTIMISATION METHDOLOGY

This section deals with the combination of reliability analysis and the Multifactor Optimisation of Structures Techniques (MOST) [1] [2], as adopted in part of this paper.

2.1 Formulation of the optimization model

The requirements for a load cell design indicate that the optimisation must involve multiple objectives and a number of design variables. Thus, an optimisation procedure is to establish a suitable method for evaluating this process; however, complex cross-relationships make it difficult to suitably appraise the design in order to yield an overall quantitative performance index which truly represents the character of the system. The optimisation tackles this problem by employing a systematic method for evaluation based on the concept of parameter profiles analysis [3]. This method evaluates a load cell design by considering many individual performance parameters for a single loading case, while also considering cost and performance.

An $m \times n$ matrix (d_{ij})—the so-called performance data matrix (PDM)—is defined by a set of performance parameters P_i (i = 1, 2,…, m) and loading case parameters C_j (j = 1, 2,…, n), respectively. The PDM is a schematic representation of a collection of data as shown in Table 1. Thus, the data point d_{ij} is the i-th performance P_i of the structure at the loading case C_j. The data points of the matrix are obtained by a finite element analysis and a reliability analysis of the structure. The matrix lists every performance of the structure at every individual loading case.

Table -1: Performance data matrix

	C_1	C_2	$\cdots$	C_n
P_1	d_{11}	d_{12}	$\cdots$	d_{1n}
P_2	d_{21}	d_{22}	$\cdots$	d_{2n}
$\vdots$	$\vdots$	$\vdots$		$\vdots$
P_m	d_{m1}	d_{m2}	$\cdots$	d_{mn}

A parameter profile matrix (PPM) is created to review the profile of the performances for different loading cases (Table 2). The data point D_{ij} in the PPM is a non-dimensional number with a range of 0–10. The PPM assesses the characteristic of the structure with respect to the actual performances at their worst acceptable limits and the best expected values of the performances.

Table -2: Parameter profile matrix

	C_1	C_2	$\cdots$	C_n
P_1	D_{11}	D_{12}	$\cdots$	D_{1n}
P_2	D_{21}	D_{22}	$\cdots$	D_{2n}
$\vdots$	$\vdots$	$\vdots$		$\vdots$
P_m	D_{m1}	D_{m2}	$\cdots$	D_{mn}

The data point D_{ij} for the one acceptable limit (e.g., lower limit) is calculated as follows:

$$D_{ij} = \frac{d_{ij} - l_{ij}}{b_{ij} - l_{ij}} \times 10 \tag{1}$$

where d_{ij} is the actual value of the performance obtained from the PDM, and l_{ij} and b_{ij} are the lower acceptable limit and the best expected value, respectively. Equation (1) is valid for $l_{ij} < d_{ij} < b_{ij}$; for $d_{ij} > b_{ij}$, $D_{ij} = 10$; and for $d_{ij} < l_{ij}$, $D_{ij} = 0$. The data point for the cases of acceptable upper limit and double acceptable limits can be calculated in a similar way.

In the optimisation model proposed, all the performance parameters, no matter whether they are considered as objectives or constraints, are collected into the PDM (Table 1). By introducing acceptable limits and best level values for each performance, a PPM (Table 2) can be founded. This procedure transforms every performance parameter into a set of goal functions in connection with loading cases. These goal functions are the elements of the PPM. In this way, a goal system is established and it brings all the performance data into the range of 0-10. For every performance parameter, the best goal is the same and its value is set to be 10. The goal functions represent closenesses to the predetermined targets (best level values of the performances). The closeness value for each parameter is an adjustable quantity related to the acceptable limit(s) and best level value of the performance. Hence, the original optimisation problem is converted to the problem of minimising the deviations between all these goal functions and their pseudo targets — quantitative value 10.

The mean and standard deviation (SD) are calculated for each parameter and loading case in each column and row in the PPM. A well-designed system should have low SDs and high mean values (close to 10). The existence of high SDs signifies that the system is likely to have significant problematic areas. Therefore, a high SD for a row indicates variable system performance at different loading cases for a particular parameter. Conversely, a high SD for a column indicates that the system is likely to have significant problematic performance for the specific loading case.

The system can be further analysed using a parameter performance index (PPI) and a case performance index (CPI), which are defined as follows:

$$\mathrm{PPI}_i = \frac{n}{\sum_{j=1}^{n} 1/D_{ij}} \quad , \quad i = 1,2,\cdots,m \quad \text{and}$$

$$\mathrm{CPI}_j = \frac{m}{\sum_{i=1}^{m} 1/D_{ij}} \quad , \quad j = 1,2,\cdots,n \tag{2}$$

When i-th parameter is very vulnerable, some data points D_{ij} of the PPM will have values close to 0 and hence the PPI_i will also close to 0. Similarly, when the system is vulnerable at the j-th loading case, CPI_j will be close to 0. The highest values for PPI and CPI are 10. PPI and CPI values that are close to 10 indicate good design, whereas values close to zero indicate poor design. The system may be reviewed by using the information in the indices, as follows:

- A comparison of PPIs indicates whether the system performs better with respect to some performances than to others.
- A comparison of CPIs shows whether the system performs better under certain loading cases than under others.

The mean values, CPIs, PPIs, and SDs provide an overall performance assessment for the system and loading cases. These indices are calculated by summing the inverse of the data points as a performance rating to avoid the effect associated with low scores being hidden by high scores. The mean values are not used directly to rate the performance. To simplify the calculations, the performance indices are categorized into the range 0–10. This enables different loading cases and parameters to be compared in order to gain an overall perspective of the characteristics of the system.

According to the matrix profile analysis, PPI and CPI are measures of the vulnerability of each performance parameter and each loading case, respectively. Hence, the integration of PPI and CPI indicates the vulnerability of a particular parameter/loading case combination. The above design synthesis concept provides a framework for formulating the quantifiable portion of a system design, from which advanced optimisation techniques can be developed. The optimisation objective function should be an overall measurement of design quality of a structural system. An overall performance index (OPI) is used to develop the overall objective function. The OPI, which takes the form of a qualitative score, can be established for the system by considering all the performances and all the loading cases. The OPI function lies in the range of 0–100. Each performance parameter and each loading case is given a weighting value according to its importance. The OPI can be expressed as follows (for the un-weighted case):

$$\mathrm{OPI} = \frac{100}{m \times n} \sum_{i=1}^{m} \sum_{j=1}^{n} \mathrm{PPI}_i \times \mathrm{CPI}_j \tag{3}$$

The OPI can be used to compare the performances of different designs under a same weighting system. The higher the OPI score, the more reliable the design would be. The OPI reflects the optimisation model (Eqn. (5) (see section 2.3)) and assembles all the objectives in the model. The overall objective function is maximised using the effective zero-order method, employing conjugate search directions [2]. The OPI is of great significance because it integrates all optimisation objectives with all design constraints in such a way that all the system performances are treated as objectives in the optimisation. Once some of the performances are improved up to their best levels, these performances will be transformed into constraints until all the performances reach their best levels or cannot be improved any more (convergence).

2.2 Reliability Analysis

A reliability loading-case index (*RLI*) is proposed which is a new development of first-order reliability-related method [1]. This method is based on the FORM developed by Hasofer and Lind (H–L) [4] and later extended by Rackwitz and Fiessler (R–F) [5]. However, in the present approach a different method is presented involving the evaluation of the *RLI*. The *RLI* reflects all the possible outcomes such as the performances and cost of the design and it can be formulated as:

$$RLI_j = \max\sqrt{\sum_i (W_{P_i} \times W\left(\frac{\sigma_{d_i}}{d_{ij}}\right))^2} \qquad (4)$$

$$i = 1,2,\cdots,m \quad \text{and} \quad j = 1,2,\cdots,n$$

where W_{P_i} is a weighting factor (range, 0–1) which reflects performance, d_{ij} is a data point which indicates the performance parameters and loading case, σ_{d_i} is the standard deviation of the performances, and W is the magnification factor applied to a particular parameter. i indicates the i-th performance, and j indicates the j-th loading case.

W is used to amplify the MSNS values to ensure they are significant when the design variable is changed, thereby enabling the results to be easily assessed. It is assumed that W cannot be equal to 0. Preliminary calculations indicate that this factor should have a value in the range of 5–7.

2.3 A reliability-related multifactor optimization model

An optimisation method "Multifactor Optimisation of Structure Techniques" (MOST) has been incorporate with reliability loading-case index (RLI) to execute a multi-factor sizing optimisation. The design problem is to minimise the structural mass, minimise the maximum stress minimise the maximum displacement, and simultaneously maximise the reliability loading-case index, subject to the design constraints under single loading case. The optimisation problem to be solved can be stated as follows:

find $X = (x_1, x_2, \ldots, x_k)$

min $\{M(X), \sigma_{\max,j}(X), \text{and } \delta_{\max,j}(X)\}$ and

max $\{RLI_j(X)\}$ (5)

s.t. $\{\sigma_{\max,j} \le \sigma_{\lim}\,;\ \delta_{\max,j} \le \delta_{\lim}\,;\ M \le M_{\lim}\,;\ RLI_j \ge RLI_{\lim}\}$

$\{x_i^{\min} \le x_i \le x_i^{\max},\ i = 1,2,\ldots,k\}$

$j = 1, 2, \ldots, n$

where k is the number of design variables, M is the structural mass, $\sigma_{\max}$ is the maximum stress of the structure, $\delta_{\max}$ is the maximum displacement of the structure, *RLI* is the reliability loading-case index, the subscript 'lim' indicates a specified performance limit for the structure, and n is the number of loading cases. $x_i^{\min}$ and $x_i^{\max}$ are the lower and upper bounds of the design variables of x_i, respectively.

The implementation flowchart of the reliability-related multifactor optimisation is illustrated in Fig. 1.

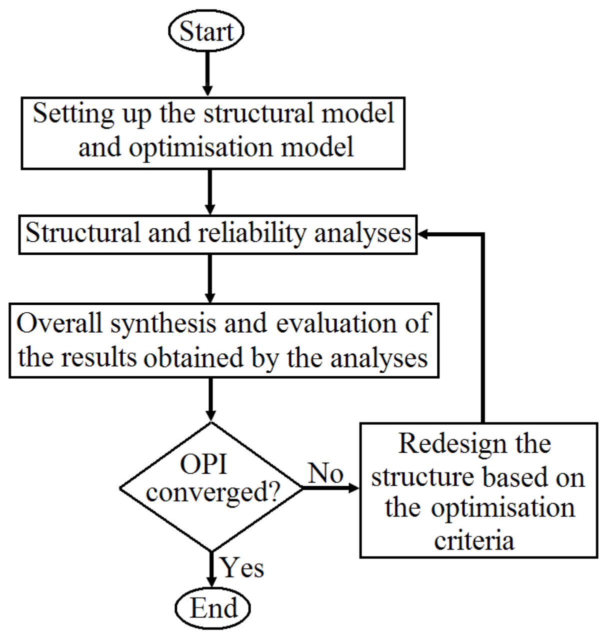

Fig -1: Implementation flow chart of the multifactor optimisation methodology

3. NUMERICAL EXAMPLE

Consider a three dimensional structural S-Type load cell with 9 nodal points are given in Table 3. The initial structure has a width (*A1*) of 50 mm and a height (*A2*) of 62 mm with the volume of 27492 mm^3, as shown in Fig. 2. The structural model annotated with 4 design variables which include width (*A1*), height (*A2*), and thickness (*A3* and *A4*). The centre hole with ϕ16.5 mm is fixed in the optimisation process where an electronic device is placed to take the strain deformation. Fig. 3 show that two M6 × 1 thread are taped at the centre of the load cell and a M6 hole is drilled toward the centre of the hole (see Fig. 3 – No.9). Since there are three M6 hole and thread in the load cell where a minimum clearance of 3 mm must be kept, the thickness of the load cell is keep constant as 12.5 mm.

Table -3: Coordinates of nodal point of initial structure

	X (mm)	Y (mm)	Z (mm)
1	0.0	0.0	0.0
2	50.0	0.0	0.0
3	50.0	43.0	0.0
4	50.0	52.0	0.0
5	50.0	62.0	0.0
6	0.0	62.0	0.0
7	0.0	19.0	0.0
8	0.0	10.0	0.0
9	25.0	31.0	0.0

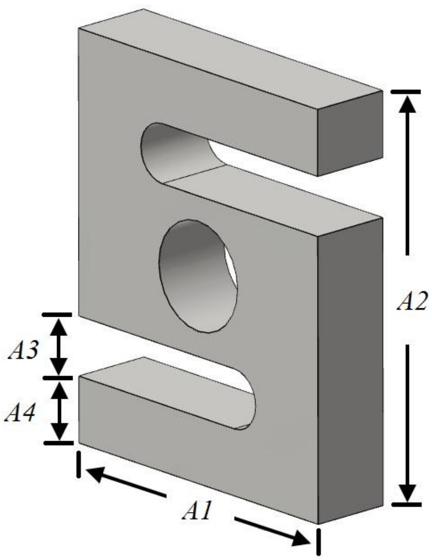

Fig -2: S-type load cell (initial design)

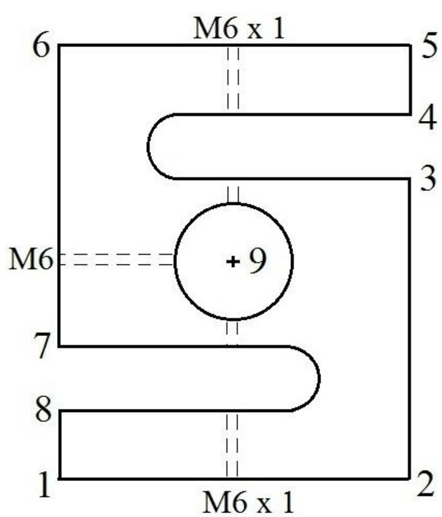

Fig -3: Initial layout of the S-type load cell structure

The initial structure of S-type load cell is modelled using finite element software in conjunction with MOST. The ANSYS SOLID92 element is used to generate the finite element model, which consists of 8407 quadrilateral elements, as shown in Fig. 4. MOST uses the 'input file' method in ANSYS to perform the optimisation process until convergence. In the optimization process, the finite element modelling is executed using ANSYS command. The 'input file' is updated the improved design during each iteration which is required by the finite element code during the optimisation.

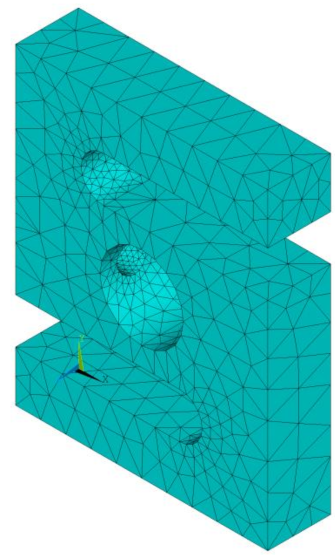

Fig -4: Finite element model of initial structure

In terms of boundary conditions, the areas of the bottom in all directions are fixed to be zero. The S-type load cell is make up of steel EN 24 with a load maximum is 2500 N (i.e., the safety of factor is up to 2.5). The S-load cell is considered at a single loading case, i.e. a uniform distributed load of P N/m^2. The uniform distribution load is defined as:

$$P = \frac{Force}{width \times thickness\ \ of\ \ load\ \ cell} \qquad (5)$$

The material density is 7840 kg/m^3, the Young's modulus is 210 GPa, the yield stress is 600 MPa, and the Poisson's ratio is 0.3. The overall objective of the design problem is to minimise the stress (consequently to minimise the maximum strain), the maximum displacement, and the structural mass, and to maximise the reliability loading-case index (RLI).

Table 4 lists the standard deviation (σ_{d_i}) and weighting factor (W_{P_i}) (see Eqn. 4) of the maximum stress, maximum displacement, structural mass, and the RLI. In this example, the magnification factor is set to be 6.67.

Table -4: The RLI design variables of individual weighing factor and standard deviation

Performances	Standard deviation (σ_{d_i})	Weighting factor (W_{P_i})
Maximum stress (MPa)	5	0.01
Maximum displacement (µm)	0.5	0.01
Mass (g)	50	0.88
RLI	-	0.10

The design is subjected to a maximum strain of 980 µ, maximum displacement of 60 µm is imposed on all nodes in all direction (x, y and z) and the structural mass is required to be less than 160 grams. From these values (980 µ, 60 µm, and 160 grams) and the equation (4), the minimum acceptable value for reliability-loading case index is calculated to be 1.834.

The optimisation of the S-load cell required n_i = 36 iterations to converge. The initial and optimised are shown in Fig. 5. The attributes of the initial and optimised designs are given in Table 5. The optimum design yields a minimal structural mass of 143 grams and a RLI of 1.365. The maximum displacement showed marked reductions from 159 to 53.3 µm. The maximum von-Mises stress also remarkably reduced from 241 to 203 MPa, in the optimised design, thereby increasing the safety of factor to ~3. Post-RLI calculations of initial and optimised designs are given in Fig. 6 – 8.

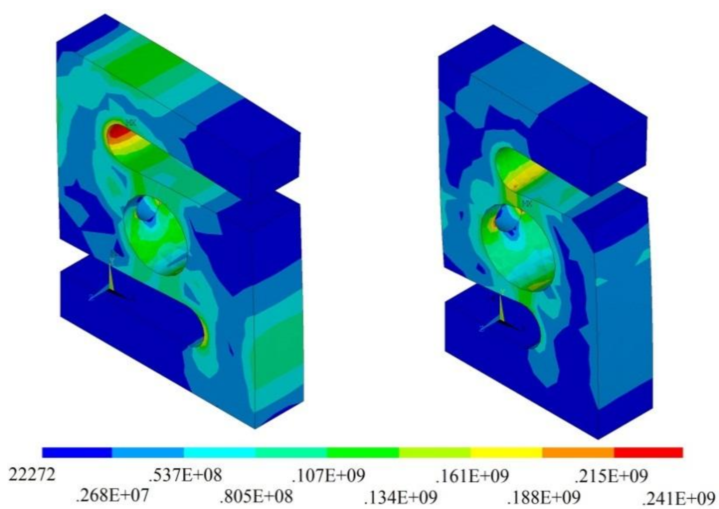

Fig -5: Distribution of von-Mises Stress (Pa) of initial (left) and optimised designs (right)

Table -5: Attributes of the initial and optimized designs of the S-type load cell

	Loading case 1	
	Initial	**Optimised**
Maximum von Mises stress (MPa)	241	203
Maximum displacement (µm)	159	53.3
Maximum strain (µ)	1150	974
Mass (g)	215	143
Reliability loading-case index RLI	1.365	2.052

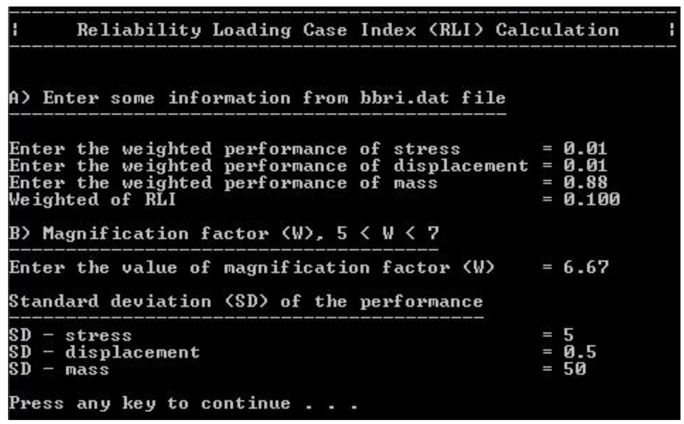

Fig -6: RLI calculations – preliminary data

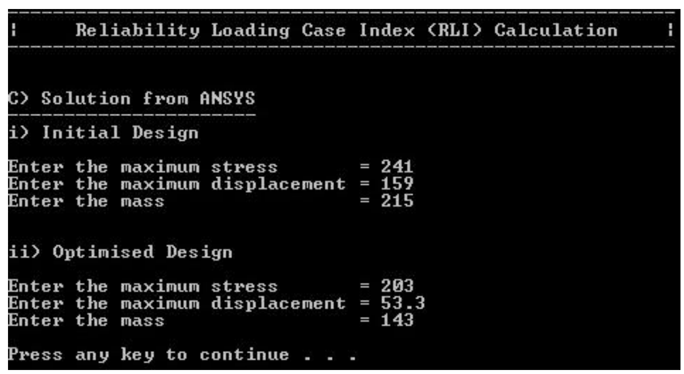

Fig -7: RLI calculation – results from ANSYS simulation

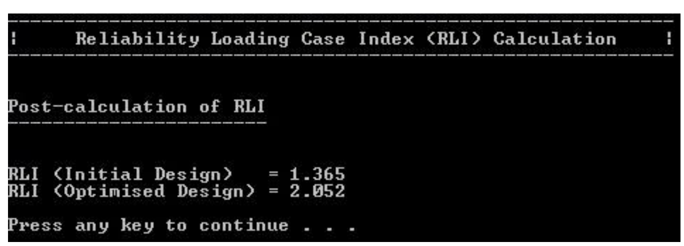

Fig -8: RLI calculation – post-result

In the S-type load cell design, a single loading case is considered. The convergence histories in Chart 1 and Chart 2 show that the trends in maximum displacement and maximum stress. Charts 1 and 2 shows that an initially sharp decrease (first iteration) in maximum displacement and maximum stress. This is because the reduction of width and height of the load cell which have a least impact on the stress and displacement. As a result, the structural mass is reduced by approximately 29% (see Chart 3). To attain convergence, the height and width of the load cell shows a marked decrease by approximately 4% and 30%, respectively.

The centre hole, ϕ16.5 mm, is fixed in the optimisation process. Fig. 9 shows that the maximum strain distribution across the width is increased by approximately 23%.

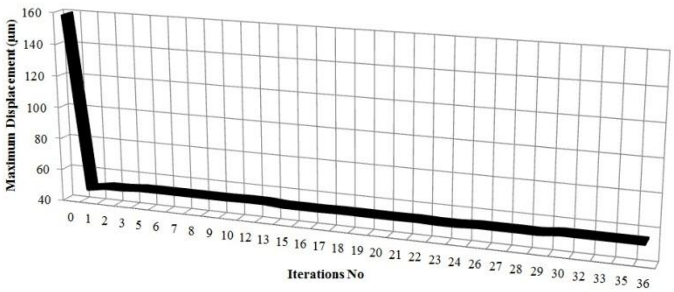

Chart -1: Optimisation convergence history of maximum displacement

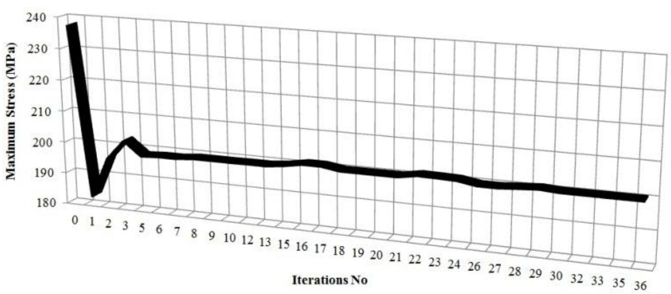

Chart -2: Optimisation convergence history of maximum stress

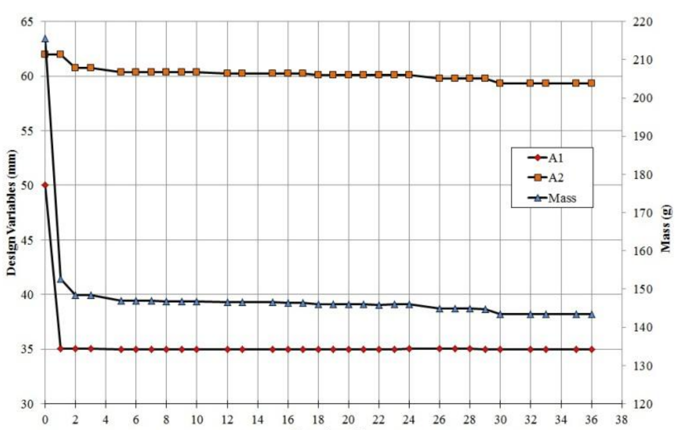

Chart -3: Optimisation convergence history of mass and design variables

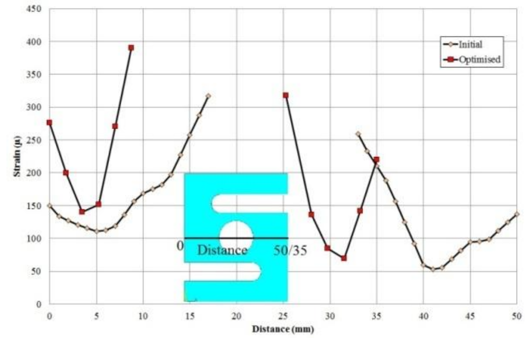

Fig -9: Strain distribution of initial and optimised structure across the width of load cell

CONCLUSIONS

A sizing and shape optimisation was presented that combines a multifactor shape optimisation with a reliability loading-case index using a parametric finite element model. The application of this method to an S-type load cell was showed an improvement of the structural performance and also indirectly increased the profit by at least 30% (i.e., reducing the mass by 30%).

Future different shape optimisation on this S-type load cell will be further analysing in order to withstand a maximum load capacity at a minimum volume.

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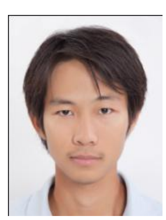
BIOGRAPHIES



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