Intelligent optimization design of specimen on sheet materials for Split Hopkinson Tensile Bar tests

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Abstract. The Split Hopkinson Tensile Bar (SHTB) is one of the most widely used methods to study the high strain rate behavior of materials. For these experiments usually dogbone-shaped sheet specimens are used. However, there’s no agreement on the exact dimensions. In the present study, mechanism of the influence of specimen responses on accuracy of SHTB experiments was investigated with finite element program ABAQUS (Explicit). Indicators which can evaluate the measurement accuracy of specimens are proposed based on this. Orthogonal test is designed to establish the sample database for back-propagation (BP) neural network, which is adopted to fit the non-linear mapping from structure parameters to accuracy indicators of specimen. Optimal design of structure for sheet specimen is obtained with Genetic Algorithm (GA) according to the fitness of individual determined by trained and qualified BP neural network. At last, numerical simulations are adopted to verify the validity of the optimal structure for sheet specimen. The result of this study can provide recommendations for specimen design and data reliability analysis in Split Hopkinson Tensile experiments.

1. Introduction

The dynamic mechanical behaviors of materials under high strain rates (10²-10⁴s⁻¹) is one of the active research areas in the field of material science. [1-4] The Split Hopkinson Tensile Bar has been commonly used to study the dynamic tension behaviors of materials since its advent. [5,6]

The connection between specimen and tensile bars is one of the crucial technologies in SHTB from the beginning, and the importance of the specimen geometry and dimensions was recognized [5-9], However, there’s no agreement existing on the exact dimensions of dogbone-shaped specimens [10-13], which are generally used in tensile Hopkinson experiments.

Some studies have been done to improve measurement accuracy by changing structural parameters of specimens, [8,14-16] but almost all the preferable structure dimensions of the specimens recommended by literatures are based on the control variable method, few studies were carried out to obtain the optimal design of specimen structure in the global scope.

In the study presented here, optimization algorithm combining orthogonal test design and BP neural network with GA is adopted to optimize the structure of sheet specimen, and the optimal structure is obtained in the global scope. Simulations are designed to verify the validity of the optimal structure of specimen.
2. Numerical simulation

2.1. Reference specimen

Figure 1 gives the typical structure of dogbone-shaped sheet specimen. Dimensions of a reference geometry are defined based on the different geometries that can be found in [17-21]: the length of the central zone \( L_1 = 8\text{mm} \), the width of this zone \( W_1 = 4\text{mm} \), the length of the glue zones \( L_2 = 18\text{mm} \), the width of the glue zones \( W_2 = 14\text{mm} \), the radius of the transition zones \( R = 3\text{mm} \) and the thickness of the specimen \( T = 0.8\text{mm} \). It’s necessary to be noted that the parameters \( L_1, W_1, L_2, W_2, R \) and \( T \) will be taken into account to optimize the structure of the specimen.

![Figure 1. Typical structure of dogbone-shaped sheet specimen](image)

2.2. Finite element model

A 3D quarter-symmetric model was used in the numerical simulation, as shown in Figure 2. The mesh is finer in the specimen, the glue layers and the Hopkinson bars ends connected to the specimen. the Hopkinson bars and the striker tube were assumed to be made of 45# steel, the glue layers were assumed to be made of epoxy bi-component adhesive [22], and the specimen was assumed to be made of 7075-T6 aluminium alloy. [23] Mechanical properties for the materials are listed in Table 1.

![Figure 2. 3D quarter-symmetric model used in numerical simulation](image)

| Mechanical properties | Density (kg/m³) | Young’s Modulus(GPa) | Poisson’s ratio | Johnson-Cook parameters |
|-----------------------|-----------------|----------------------|----------------|------------------------|
| 45# steel             | 7850            | 210                  | 0.30           | -                      | -                      | -                      |
| Epoxy adhesive        | 1800            | 1.99                 | 0.36           | -                      | -                      | -                      |
| AA7075                | 2800            | 71                   | 0.33           | 473                    | 210                    | 0.3138                 | 0.033                 |

2.3. Indicators for measurement accuracy of specimens

2.3.1. Duration to reach stress equilibrium (DRSE). A meshed quarter-symmetric model of specimen is shown in Figure 3. A path, between the front end and the back end of central section, was marked along the symmetry axis of the whole specimen. DRSE was defined to represent the interval, which from the moment that the tensile wave just reaches the back end of central section to the moment that the relative deviation of axial stresses at the front end and the back end of central section begins to be less than 5%.
2.3.2. Level of non-axial stress (LNS). The ratios of non-axial stress to axial stress at the moment when the maximum axial stress is reached at the center of the specimen were calculated along the path, as shown in Figure 4, and the concept LNS was defined to represent the average of the ratios distributing along the path.

![Meshed quarter-symmetric model of specimen](image)

**Figure 3.** Meshed quarter-symmetric model of specimen

![The ratios of non-axial stress to axial stress along the path at the moment when the maximum axial stress is reached at the center of the specimen](image)

**Figure 4.** The ratios of non-axial stress to axial stress along the path at the moment when the maximum axial stress is reached at the center of the specimen

![The distribution of the axial strain along the path](image)

**Figure 5.** The distribution of the axial strain along the path

2.3.3. Deformation homogeneity (DH). Figure 5 gives the distribution of the axial strain along the path, it can be seen that the axial strain along the path is also non-homogeneous. DH was defined to represent the variance of the axial strain along the path. It can indicate the uniformity of the strain distribution along the path thus the homogeneity of the specimen deformation.

2.3.4. Deformation contribution of transition zones (DCTZ). The deformation of the central section (defined as the relative displacement of the two points delimiting the central section, see in Fig 2), the deformation of the transition zones, the deformation of the total specimen (the two transition zones along with the central section) and the contribution of the deformations of the transition zones relative to the total specimen deformation is given in Table 2.
Table 2. Deformation of the sections and the contribution of the transition zones.

| Deformation (mm)       | Contribution of transition zones |
|------------------------|----------------------------------|
| Central section        | Transition zones                 | Total specimen |
| 1.01263                | 0.00702                           | 1.01965        | 0.69%   |

3. Intelligent optimization

3.1. Sample database based on orthogonal test design

An orthogonal L25(5)^6 test was designed to establish the sample database of structural parameters for BP neural network. As seen from Table 3, the numerical simulations were carried out with 6 factors and 5 levels, namely L1 (see in Fig. 2; 6, 7, 8, 9, 10mm), W1 (3, 3.5, 4, 4.5, 5mm), L2 (16, 17, 18, 19, 20mm), W2 (13, 14, 15, 16, 17mm), R (2, 2.5, 3, 3.5, 4mm) and T (0.4, 0.6, 0.8, 1.0, 1.2mm). Data in the last four columns of Table 3 is the indicators of measurement accuracy for the corresponding specimens obtained by numerical simulations with ABAQUS (Explicit).

Table 3. Sample database based on orthogonal design

| Test | Structural parameters (mm) | DRSE | LNS | DH | DCTZ |
|------|---------------------------|------|-----|----|------|
| L1   | W1 | L2 | W2 | R | T |
| 01   | 6  | 3  | 16 | 13 | 2  | 0.4 | 18.00 | 0.0287 | 0.0020 | 0.0090 |
| 02   | 6  | 3.5 | 17 | 14 | 2.5 | 0.6 | 18.00 | 0.0328 | 0.0025 | 0.0086 |
| 03   | 6  | 4  | 18 | 15 | 3  | 0.8 | 18.61 | 0.0348 | 0.0023 | 0.0061 |
| 04   | 6  | 4.5 | 19 | 16 | 3.5 | 1.0 | 18.85 | 0.0353 | 0.0021 | 0.0107 |
| 05   | 6  | 5  | 20 | 17 | 4  | 1.2 | 20.80 | 0.0339 | 0.0030 | 0.0107 |
| 06   | 7  | 3  | 17 | 15 | 3.5 | 1.2 | 21.45 | 0.0188 | 0.0016 | 0.0084 |
| 07   | 7  | 3.5 | 18 | 16 | 4  | 0.4 | 21.00 | 0.0194 | 0.0015 | 0.0028 |
| 08   | 7  | 4  | 19 | 17 | 2  | 0.6 | 21.00 | 0.0353 | 0.0031 | 0.0046 |
| 09   | 7  | 4.5 | 20 | 13 | 2.5 | 0.8 | 21.50 | 0.0373 | 0.0029 | 0.0070 |
| 10   | 7  | 5  | 16 | 14 | 3  | 1.0 | 22.00 | 0.0380 | 0.0031 | 0.0067 |
| 11   | 8  | 3  | 18 | 17 | 2.5 | 1.0 | 22.50 | 0.0191 | 0.0015 | 0.0164 |
| 12   | 8  | 3.5 | 19 | 13 | 3  | 1.2 | 23.00 | 0.0215 | 0.0015 | 0.0189 |
| 13   | 8  | 4  | 20 | 14 | 3.5 | 0.4 | 22.79 | 0.0228 | 0.0016 | 0.0141 |
| 14   | 8  | 4.5 | 16 | 15 | 4  | 0.6 | 22.81 | 0.0244 | 0.0018 | 0.0173 |
| 15   | 8  | 5  | 17 | 16 | 2  | 0.8 | 22.81 | 0.0436 | 0.0032 | 0.0044 |
| 16   | 9  | 3  | 19 | 14 | 4  | 0.8 | 24.00 | 0.0133 | 0.0011 | 0.0208 |
| 17   | 9  | 3.5 | 20 | 15 | 2  | 1.0 | 23.50 | 0.0265 | 0.0017 | 0.0056 |
| 18   | 9  | 4  | 16 | 16 | 2.5 | 1.2 | 24.00 | 0.0249 | 0.0018 | 0.0048 |
| 19   | 9  | 4.5 | 17 | 17 | 3  | 0.4 | 24.31 | 0.0220 | 0.0019 | 0.0082 |
| 20   | 9  | 5  | 18 | 13 | 3.5 | 0.8 | 24.00 | 0.0289 | 0.0020 | 0.0082 |
| 21   | 10 | 3  | 20 | 16 | 3  | 0.6 | 25.20 | 0.0140 | 0.0012 | 0.0072 |
| 22   | 10 | 3.5 | 16 | 17 | 3.5 | 0.8 | 25.20 | 0.0164 | 0.0013 | 0.0093 |
| 23   | 10 | 4  | 17 | 13 | 4  | 1.0 | 25.00 | 0.0179 | 0.0012 | 0.0139 |
| 24   | 10 | 4.5 | 18 | 14 | 2  | 1.2 | 25.01 | 0.0318 | 0.0021 | 0.0024 |
| 25   | 10 | 5  | 19 | 15 | 2.5 | 0.4 | 24.00 | 0.0310 | 0.0022 | 0.0051 |

3.2. Combine BP neural network with Genetic algorithm(GA)

In this paper, the fitness that can evaluate the quality of individuals are determined by neural network. Optimization strategy combining orthogonal test and BP neural network with GA is shown in Figure 6.

Based on the accuracy indicators forecasted by neural network, the objective function of GA was constructed as shown in expression 1. Where I1, I2, I3, I4 are the values of the accuracy indicators DRSE, LNS, DH, DCTZ, mapped from random structural parameters matrix [l1, w1, l2, w2, r, t], respectively; I1, I2, I3, I4 are the values of the corresponding indicators got from the last four columns of Table 3, k=25; ObjV is the value of objective function.

\[
ObjV = \frac{I_1}{\sum_{i=1}^{k} \frac{I_1}{k}} + \frac{I_2}{\sum_{i=1}^{k} \frac{I_2}{k}} + \frac{I_3}{\sum_{i=1}^{k} \frac{I_3}{k}} + \frac{I_4}{\sum_{i=1}^{k} \frac{I_4}{k}}
\]
4. Optimization results and analysis

4.1. Optimization results
The optimal individual (the minimum objective value) in each generation of GA was recorded, as shown in Figure 7. As can be seen, the better individuals were constantly chosen in the early stages of evolution and the minimum objective value reduced sharply at the same time. However, the evolution process tends to be stable after the 30th generation, in fact, the minimum objective value in each generation remained unchanged after the 44th generation. So, it can be sure that the GA can obtain the optimal individual before the end of evolution process. The optimal individual, which represent the optimal structure of specimen, is shown in the following expression 2 (unit: mm).

\[
\begin{bmatrix}
L_1 & W_i & L_2 & W_z & R & T
\end{bmatrix}^T = \begin{bmatrix} 9.8 & 3.9 & 19.4 & 16 & 2.9 & 1.1 \end{bmatrix}^T
\]  

(2)

4.2. Analysis of optimized specimen
According to the results of optimization, the optimal structure of specimen which can achieve the most accurate measurements is shown in Figure 8.

Table 4 gives the comparison of each accuracy indicator between the optimized specimen and reference specimen. As can be seen, compared to the reference specimen, the optimized specimen takes longer to reach stress equilibrium, however the optimized specimen has a lower level of non-axial stress and the deformations in it are more homogeneous. What’s more, for the optimized specimen, less deforming contribution was made by transition zones.
Figure 7. The optimal individual in each generation of GA

Figure 8. The structure of the specimen after optimization

Table 4. The comparison of the indicators between referenced and optimized specimens

| Indicator | Optimize | Reference | Increase or decrease |
|-----------|----------|-----------|----------------------|
| DRSE      | 24.75    | 22.81     | 8.5%↑                |
| LNS       | 0.0220   | 0.0249    | 11.6%↓               |
| DH        | 0.0015   | 0.0018    | 16.7%↓               |
| DCTZ      | 0.38%    | 69%       | 44.9%↓               |

5. Conclusions
The indicators for measurement accuracy of the specimens were proposed according to the results of numerical simulations of the Split Hopkinson tensile test adopting the specimen with reference dimensions. Based on the indicators, the optimal structure of the specimen was obtained by the optimization algorithm which combines orthogonal test design and BP neural network with GA. The following conclusions were summarized.

Valid non-linear mapping between structural parameters and accuracy indicators can be fitted by BP neural network, and the synergistic optimization algorithms consisting of orthogonal test design, BP neural network and GA are valid and practical in the optimization design of specimen structure.

The parameters of the optimal structure of specimen are as follows: the length of the central section L1=9.8mm, the width of the central section W1=3.9mm, the length of the glue zones L2=19.4, the width of the glue zones W2=16, the radius of the transition zones R=2.9, the thickness of the specimen T=1.1mm.

It takes longer for the optimized specimen to reach stress equilibrium, the indicator duration to reach stress equilibrium increased by 8.5% compared to the reference specimen. The non-axial stress in the optimized specimen is in lower level, compared to the referenced specimen, the indicator level of non-axial stress reduced by 11.6%. The deformations in the optimized specimen are more homogeneous than those in the reference specimen, the indicator deformation homogeneity reduced by
16.7%. The relative deformation of the transition zones of the optimized specimen is smaller, the indicator deforming contribution of transition zones reduced by 44.9% compared to that before optimization.

It should be emphasized that the above conclusions are material dependent. In fact, the duration to reach stress equilibrium, the level of non-axial stress, the deformation homogeneity and the deforming contribution of transition zones are determined by the mechanical strain rate dependent material behaviour. Thus, the dimension parameters for the optimal specimen structure is only valid for materials having a behaviour comparable with the material considered here.

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