Multiple-Criteria Evaluation of Thin-Walled Energy-Absorbing Structures of Train Under Fuzzy Environment: Modeling and Algorithm

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ABSTRACT
High-speed train is of great significance in the modern comprehensive transportation system. Bio-inspired engineering design, with the excellent structural and mechanical properties of the biological systems, has been a widespread concern in the design of thin-walled energy-absorbing structures for high-speed trains. However, different structural characteristics have significant effects on the performance of crashworthiness and lightweight level. Collaboration matching of performance between design and operational processes considering the engineering requirements has become an urgent problem. This study constructs the finite element model of the horsetail-bionic thin-walled energy-absorbing structure, which is inspired by horsetail’s structural characteristics. An existing high-speed train is set as the empirical case. The effects of the number of cross-section configurations on the performances of crashworthiness and light level are explored under the condition of train collision. A hybrid decision-making methodology that combines fuzzy DEMATEL and TODIM is proposed. The result shows the horsetail-bionic thin-walled structure with six-floor plates is the optimal alternative considering the multiple criteria. In addition, comparison with the existing methods and sensitivity analysis are conducted to validate the reliability of this proposed approach. This study provides an effective decision support tool for crashworthiness evaluation or structural feature selection of thin-walled structures.

INDEX TERMS Energy absorbing structures, transportation, high-speed train, evaluation algorithm, sustainability.

I. INTRODUCTION
Passive safety protection of trains has been carried out with continuous extension from both the academic world, transport agency and manufacturers in recent years, due to the train collision inevitably will lead to severe casualties and property losses [1], [2]. Based on the International Union of Railways, more than 15000 accidents occurred, including collisions and derailments, from 2014 to 2019, resulting in 9,415 deaths and 15,708 injuries [3]. Efforts to develop safety protection technology have important research meanings. In addition, based on the International Energy Agency, the share of energy used in the global transportation industry has risen from 23.2% in 1973 to 28.8% in 2016, second only to industry, and is expected to reach 26.6% in 2040. The problem of energy conservation and emission reduction in the transportation industry has become increasingly prominent [4], [5]. Thus, collaboration matching of performance between safety and sustainability has become an urgent problem to be solved.

Energy-absorbing structures (EASs) have essential vehicle crashworthiness [6]. At present, the researches of EASs can be divided into two categories as follows: the first is single-cell EASs, the second is multi-cell EASs [7], [8]. Compared to single-cell one, the multi-cell EASs have more widespread
implications in a broad range of applications because of their excellent energy absorption capacity [9]. In recent years, a series of systemic theoretical explorations and literature reports for multi-cell EASs have been investigated employing experiments, simulation, and optimizations [10], [11]. For example, Zhang et al. proposed a multi-element thin-walled aluminum EAS for high-speed trains and constructed the finite element model of this structure. The collision performance analysis and multi-objective robust optimization of this structure were conducted [12], [13]. Wang et al. presented a compound thin-walled ESA that combined the theory of origami design and conducted multi-objective robust optimization to minimize the peak crushing force (PCF) and maximize specific energy absorption (SEA) [14]. Ma et al. put forward a bio-inspired multi-cell corrugated EAS, which contains an inner rib and bellows. Two inner ribs with various sections were designed as well as the crashworthiness of this structure was analyzed [15]. In summary, multi-cell EASs possess excellent performance in energy absorption and are lightweight [16], [17]. However, how to obtain the optimal cross-section of thin-walled structures is still a challenge.

Bio-inspired design of thin-walled EASs has been used in a broad range of applications to obtain remarkable crashworthiness, e.g., energy absorption, due to plants/animals revealing many excellent structures with high performances of lightweight level, strength, and energy absorption in nature [18]. In recent years, numerous bio-inspired multi-cell structures have been imitating various biological structures [19], [20]. Zou et al. put forward a hybrid bio-inspired multi-cell EASs based on the features of bamboo vascular structures. The results obtained by simulated analysis indicated that the SEA of this structure in transverse and axial impact loads are all enhanced [21]. Feng et al. proposed three bio-inspired EASs and studied the influence of different bionic components on energy absorption performance. The results indicated that the bio-inspired EASs, on account of vascular bundle structures’ characteristics had the best energy absorption performance [22]. For EASs of high-speed trains, the most important and commonly used crashworthiness performance is EA, PCF, and mass (M). However, the performance of sustainability, i.e., M, and the performance of crashworthiness, i.e., EA and PCF, of EASs are primarily related to the inherent properties of the structure. Selecting an optimal structural feature according to conflicting performances and engineering requirements has become an important research topic, which can be treated as a typical multi-attribute decision making problem.

There are a lot literatures about the application of thin-wall EASs of bionic design in engineering crashworthiness. However, it is difficult to measure the advantages and disadvantages of different structures. Therefore, it’s necessary to provide a set of methods to test the performance of different bionic thin-wall EASs in engineering applications, which can provide positive help to select the most suitable bionic structure and effectively reduce the use cost. However, few studies have conducted scientific selection analysis for different bionic thin-wall EASs. Based on this, this study takes the horsetail structure as an example to carry out the research on the selection of bionic thin-walled EASs structures. Through establishing the horsetail biomimetic thin-wall EASAs finite element model, the performance of sustainability, i.e., lightweight level and the performance of crashworthiness, i.e., EA and PCF, of six structures with different cross-section configurations are analyzed under the condition of train collision. A hybrid collaboration matching methodology that combines fuzzy DEMATEL and TODIM is put forward. An example of a train verifies the validity of the method. The robustness of the monitoring results is analyzed and discussed, and the actual influence on rail transit is summarized. The research shows that this study offers an efficient decision support tool for crashworthiness evaluation or structural feature selection of thin-walled structures.

In comparison with the previous studies, three distinctive contributions are summarized as follows: 1) exploring the effects of the number of cross-section configurations on the performances of crashworthiness and light level under the condition of a train collision; 2) presenting a hybrid decision-making methodology for solving the problem of multiple-criteria evaluation of thin-walled energy-absorbing structures; 3) conducting the comparison and sensitivity analysis to validate the reliability of this proposed approach.

The organizational structure of this paper is as follows: Section 2 constructs the finite element model of the horsetail-bionic thin-walled EASs and analyzes the crashworthiness performance of six structures with various cross-section configurations. In Section 3, we develop a hybrid evaluation methodology, combining fuzzy DEMATEL and TODIM. An existing train is taken as an example to verify the availability of the model and the solution method described in Section 4. It is analyzed and discussed in Section 5. In the end, the conclusions of this study are drawn in Section 6.

II. MODELING AND PERFORMANCE ANALYSIS

A. STRUCTURAL FEATURES OF HORSETAIL

As herbaceous perennial plants, Horsetails need to survive in all kinds of harsh environments [18]. Therefore, the interior structures of the horsetail plant also contain cylindrical hollow multi-cell structures, which can help withstand strong lateral loading conditions from environmental factors, e.g., wind and rain. The structure of several different horsetail plants, including marsh, field, wood, variegated, and shore, is shown in Fig. 1 [23]. These interior structural features of the horsetail served as an inspiration to develop the new-style EASs with better crashworthiness performance. The cross-sections of horsetail-bionic thin-walled EASs can be designed according to the interior structural features of horsetail, as shown in Fig. 2. This structure applies cylindrical hollow multi-cell design philosophy, and a floor plate connects the outer circle and the inner circle of this structure.
B. MODEL OF THE HORSETAIL-BIONIC THIN-WALLED EASs

The finite element model of the horsetail-bionic thin-walled EASs is built, as shown in Fig. 3. In this model, the material for horsetail-bionic thin-walled EASs is aluminum alloy AlMg0.5F22. The material parameters are: density \( \rho = 2.7 \times 10^3 \text{ kg/m}^3 \), Young’s modulus \( E = 68.566 \text{ GPa} \), Poisson’s ratio \( \nu = 0.29 \), Initial yield strength \( \sigma_y = 227 \text{MPa} \), Tangential modulus of elasticity \( E_t = 321 \text{MPa} \). Furthermore, the strain rate sensitivity of aluminum alloy is weak, and the effect of strain rate is ignored [24], [25]. The explicit non-linear finite element software LS-DYNA is used to research the fragmentation behavior of the horsetail-bionic thin-walled EASs.

To verify the effectiveness of this model, a comparison between this built model and the existing model is conducted under the simulation condition, as illustrated in Fig. 4 [23]. One end of the horsetail-bionic thin-walled EASs was fixed on the rigid wall, and the other end was impacted by a punch of 1000 kg with an initial speed of 15 m/s. The length is 200 mm, and the outer diameter is 80 mm. The internal diameter is 49.54 mm. The thickness \( t = 2.53 \text{ mm} \). The element size was chosen as 2.0 mm in the subsequent finite element models of the horsetail-bionic thin-walled EASs. The resulting crushing force-displacement thin-walled EASs can be obtained, as shown in Fig. 5.
According to the result of Fig. 5, the deformation process and the simulation result are in good agreement with the previous studies. Based on the authentication, the finite element model of the horsetail-bionic thin-walled EASs, as shown in Fig. 3, can be applied to the following researches.

C. PERFORMANCE ANALYSIS OF SAFETY AND SUSTAINABILITY

In this sub-section, six horsetail-bionic thin-walled EASs (alternatives) with different cross-section configurations are designed, which have different floor plates. The finite element models of six alternatives are constructed in LS-DYNA as shown in Fig. 6.

There are many indexes to evaluate the crashworthiness performance of horsetail-bionic thin-walled EASs, e.g., $EA$, $PCF$, mean crushing force ($MCF$), crushing force efficiency ($CFE$), and undulation of load-carrying capacity ($ULC$) [26]. The most commonly used in optimizations/evaluations processes are $EA$, $PCF$ and $M$. The $EA$ specifies the energy absorption, and high $EA$ means high energy absorption capacity [27]. The high $PCF$ always brings high acceleration, which will increase the injury to passengers. $M$ represents the lightweight level of the structure, and small $M$ means suitable lightweight [28]. Therefore, $EA$ and $PCF$ are selected as the crashworthiness factors and $M$ as the sustainability factor in this study. In addition, the simulation condition is set, as shown in Fig. 7. One end of the horsetail-bionic thin-walled EASs is fixed on the rigid wall, and a punch of 600 kg impacts the other end at a constant speed of 2 m/s. The length is 110 mm, and the outer diameter is 100 mm. The thickness $t = 0.8$ mm. We use a surface mesh model. The element size is chosen as 3.0 mm in the subsequent finite element models. In this model, the material for horsetail-bionic thin-walled EASs is aluminum alloy 6061-O. The material parameters are: density $\rho = 2.7 \times 10^3$ kg/m$^3$, Young’s modulus $E = 68.0$ GPa, Poisson’s ratio $\nu = 0.33$. The effective stress-strain curve of aluminum alloy 6061-O refers to [23]. Furthermore, the strain rate sensitivity of aluminum alloy is weak, and the effect of strain rate is ignored [24], [25]. The results of the simulation can be obtained as shown in Table 1.

According to Table 1, some conclusions can be concluded as follows: 1) the number of floor plates has a great impact on the crashworthiness of horsetail-bionic thin-walled EASs, and with the increase of the number of floor plates, the crashworthiness factors, including $EA$, $PCF$, and the sustainability factor, i.e., $M$, are also enhanced; 2) the variation trends of the three crashworthiness factors are contradictory, e.g., while the performance of $EA$ is improved, the performance of $PCF$ is decreased, so it is difficult to make an effective evaluation. Thus, an efficient decision-making method for evaluating the crashworthiness of EASs is needed.

III. THE HYBRID OPTIMIZATION METHODOLOGY

A. FUZZY DEMATEL METHOD

As a synthetical method, DEMATEL can obtain causality from complex indicators via graphs [29], [30]. Besides, the Dematel method can consider the correlation between indicators, which can reduce the weight error caused by the difference of indicators. To solve the vagueness and imprecision in the judgment process of experts, the fuzzy set theory can be applied in this method [31], [32]. Triangular and trapezoidal

| Alternative | $EA$ (kJ) | $PCF$ (kN) | $M$ (kg) |
|-------------|-----------|------------|----------|
| Alternative 1 | 1160.18 | 52.14 | 0.1480 |
| Alternative 2 | 1400.35 | 57.50 | 0.1569 |
| Alternative 3 | 1540.14 | 64.03 | 0.1658 |
| Alternative 4 | 1741.04 | 69.83 | 0.1747 |
| Alternative 5 | 1907.92 | 77.45 | 0.1836 |
| Alternative 6 | 2106.14 | 82.78 | 0.1926 |
fuzzy numbers are two types of fuzzy numbers commonly used [33, 34]. In this study, combining the fuzzy theory, the DEMATEL method can achieve simplicity of calculation and features. The following shows the specific procedure of the fuzzy DEMATEL method [35]:

**Step 1:** Construct the linguistic assessment influence matrix.

The linguistic scale of the assessment influence matrix is designated as shown in Table 2. Notation $x_{ij}$ represents the influence of indicator $i$ on indicator $j$. In the direct infeclation matrix, the value of diagonal element (i.e. $i = j$) is zero (i.e. 0,0,0). Through the evaluation of $k$th expert, a non-negative $n \times n$ matrix can be constructed as $X^k = [x^k_{ij}]$, where $k$ represents the number of each expert $(1 \leq k \leq H)$.

**Step 2:** Obtain the fuzzy initial direct-relation matrix.

Through the $H$ respondents, a fuzzy initial direct-relation matrix is established. The triplet $(l, m, n)$ is used to represent fuzzy numbers. The fuzzy initial direct-relation matrix $A = [a_{ij}]_{n \times n}$ can be computed by Eq. (1):

$$a_{ij} = \frac{\sum_{k=1}^{H} x^k_{ij}}{H}$$

where $x^k_{ij}$ represents the influence degree of the indicator “$i$” to indicator “$j$” assessed by $k$th expert. In addition, following the defuzzification procedure of the weighted average method, these fuzzy numbers can be converted to the crisp number, as shown in Eq. (2):

$$x^k_{ij} = \frac{1}{6} (l + 4m + n)$$

**Step 3:** Obtain the normalized initial direct-relation matrix $[N]$. The calculation procedure of $[N]$ can be expressed as Eqs. (3) and (4):

$$[N]_{n \times n} = S \times [A]_{n \times n}$$

where $S = \min \left[ \frac{1}{\max \sum_{j=1}^{n} |a_{ij}|}, \frac{1}{\max \sum_{i=1}^{n} |a_{ij}|} \right]$

**Step 4:** Calculate the total relation matrix $T$. The calculation process of $T$ can be expressed as Eq. (5):

$$[T] = [N] \times [(I - N)]^{-1}$$

**Step 5:** Calculate the causal arguments $R$ and $C$. The calculation processes of $R$ and $C$ are shown in Eqs. (6) and (7):

$$R = (r_{ij})_{n \times 1} = \sum_{i=1}^{n} t_{ij} \quad \forall j$$

$$C = (c_{ij})_{n \times 1} = \sum_{i=1}^{n} t_{ij} \quad \forall i$$

where, $r_{ij}$ is formed by the superposition of the $i$th row in the matrix $[T]$, which is constructed of direct/indirect effects of the indicator “$i$” on others; $c_{ij}$ is formed by the superposition of the $i$th row in the matrix $[T]$, which is constructed of direct/indirect effects that indicator “$ij$” has received from others.

**Step 6:** The center degree and causal degree can be obtained by the data set forming by prominence ($P_i$) and net effect ($E_i$):

$$P_i = r_{ij} + c_{ij} \quad \forall i, j$$

$$E_i = r_{ij} - c_{ij} \quad \forall i, j$$

**Step 7:** Calculate the weight vector of the risk sub-criteria. The calculation processes are shown in Eqs. (10) and (11).

$$W_j = \sqrt{P_i^2 + E_i^2}$$

$$\omega_j = \frac{W_j}{\sum_{i=1}^{n} W_j}, \quad (j = 1, 2, \ldots, n)$$

where, $W_j$ shows the weight vector for each sub-criterion. $\sum_{i=1}^{n} W_j$ represents the sum of the weight vector for sub-criteria.

**B. TODIM METHOD**

As a method considering the risk aversion of decision-makers, TODIM has received wide attention, which can better describe the bounded rational behavior of decision-makers. Based on prospect theory, TODIM method is used to determine the sort of alternatives by comparing the overall dominance of one alternative with others [36]. The following shows the specific steps of TODIM method [37]:

**Step 1:** Formulate the decision matrix of each alternative. Suppose there are $m$ alternatives and $n$ evaluation indicators in the process of decision-making, which can be expressed by $A = (A_1, A_2, \ldots, A_m)$ and $C = (C_1, C_2, \ldots, C_n)$, respectively. The decision matrix can be expressed by $R = [r_{ij}]_{m \times n}$. The $r_{ij}$ means the value of $j$th indicator on the $i$th alternative.

**Step 2:** Establish the normalizing decision matrix and calculate the relative weight of evaluation indicators. The normalized matrix, that is $F = [f_{ij}]_{m \times n}$, can be calculated.

| Linguistic Scale | Equivalent Fuzzy Numbers |
|------------------|--------------------------|
| No influence (No)| (0.00, 0.00, 0.25)       |
| Low influence (L) | (0.00, 0.25, 0.50)       |
| Medium influence (M) | (0.25, 0.50, 0.75)   |
| High influence (H) | (0.50, 0.75, 1.00)       |
| Very high influence (VH)| (0.75, 1.00, 1.00) |
by the normalization process in [1]. In addition, the relative weight of the evaluation indicator $C_j$ is obtained by the formula $w_{jr} = w_j / w_r$, in which $w_r$ satisfies $w_r = \max \{ w_j | j \in n \}$. 

Step 3: Compute the relative dominance of each evaluation indicator. In this study, the deviation of different alternatives can be calculated by the distance measure, which can unify the decision matrix. The dominance function $\varphi_j(A_i, A_k)$ represents the superiority of the alternative $A_i$ over alternative $A_k$ under the indicator $C_j$, which can be constructed by Eq. (12).

$$
\varphi_j(A_i, A_k) = \begin{cases} 
\frac{w_{jr}}{n} d (f_{ij}, f_{kj}) & f_{ij} > f_{kj} \\
0 & f_{ij} = f_{kj} \\
- \frac{1}{\theta} \sum_{j=1}^{n} \frac{w_{jr}}{w_{jr}} d (f_{ij}, f_{kj}) & f_{ij} < f_{kj}
\end{cases}
$$

(12)

where, $f_{ij} > f_{kj}$ represents income; $f_{ij} < f_{kj}$ represents loss; $\varphi$ represents the loss attenuation coefficient, and in this study, we set $\varphi > 0$.

Step 4: Obtain the overall dominance of each alternative. Form the dominance matrix $\varphi_j$ by using the indicator $C_j$, as follows:

$$
[\varphi_j]_{ik} = \left( \begin{array}{cccc}
\varphi_{i1} & \varphi_{i2} & \cdots & \varphi_{im} \\
\varphi_{21} & \varphi_{22} & \cdots & \varphi_{2m} \\
\vdots & \vdots & \ddots & \vdots \\
\varphi_{m1} & \varphi_{m2} & \cdots & \varphi_{mm}
\end{array} \right)
$$

(13)

In addition, the overall dominance of the alternative $A_i$ relative to another alternative $A_k$ can be expressed as $\delta(A_i, A_k)$. The calculation process of the overall dominance can be expressed as Eq. (14).

$$
\delta(A_i, A_k) = \sum_{j=1}^{n} \varphi_j(A_i, A_k)
$$

(14)

Step 5: Obtain the synthetical ranking values $\xi_i$ of each alternative. The value of $\xi_i$ can be calculated by the standardizing process of the overall dominance matrix, as shown in Eq. (15).

$$
\xi_i = \frac{\sum_{k=1}^{m} \delta(A_i, A_k) - \min_{i} \sum_{k=1}^{m} \delta(A_i, A_k)}{\max_{i} \sum_{k=1}^{m} \delta(A_i, A_k) - \min_{i} \sum_{k=1}^{m} \delta(A_i, A_k)}
$$

(15)

IV. CASE STUDY

A. BACKGROUND

The common trend of world transportation development is high speed, large capacity, low energy consumption, light pollution, etc. [13]. In this sub-section, the application of the decision method is verified with the thin-walled structure at the front of the fuxing high-speed train as the engineering background, as shown in Fig. 8. The structure is an essential part of vehicle safety, which dissipates collision energy in a collision accident and maintains the integrity of the driver’s workspace.

B. METHOD

1) STAGE 1: CONSTRUCT THE SIX HORSETAIL-BIONIC THIN-WALLED EASs

Based on the finite element models as shown in Fig. 6, carrying out simulation analysis of six horsetail-bionic thin-walled EASs under the condition of train collision (as shown in Fig. 7) utilizing the finite element models of each structure as shown in Fig. 6. The crashworthiness factor, including $PCF$, $EA$, and $M$, can be obtained, and the result will be viewed as the elements in the decision matrix in the decision-making process. Besides, the relation between each crashworthiness factor and the number of floor plates can be obtained.

2) STAGE 2: USE THE FUZZY DEMATEL METHOD TO CALCULATE THE WEIGHT OF CRASHWORTHINESS FACTORS

Construct the linguistic assessment influence matrix of each evaluation factor by qualified experts utilizing the Linguistic scale showed in Table 2. In this stage, the evaluation factor includes $PCF$, $EA$, and $M$, the crashworthiness one. The final linguistic assessment influence matrix is constructed by computing the average mathematical value of the quantization matrix obtained by each expert. The weight vector of each evaluation factor can be calculated by the procedure of the fuzzy DEMATEL method.

3) STAGE 3: OBTAIN THE OPTIMAL ALTERNATIVE BY THE TODIM METHOD

Compared with other traditional methods, the decision matrix for six horsetail-bionic thin-walled EASs is constructed by numerical simulation rather than the decision-making process by expert score, which can evade the subjectivity in the process of building the decision matrix. The $\xi_i$ value of each alternative can be obtained using the calculation process of the TODIM method. Note that the larger the index $\xi_i$, the better the performance.
linguistic assessment influence matrix, is computed by three experts from different industries, e.g., university scholars and corporate architects, through the questionnaire form to survey, as shown in Table 3. The survey was conducted in January 2021. Compared with the data collected from the three questionnaires, the error rate is 3.2%. Therefore, the results are trustworthy. The weight vectors of the $EA$, $PCF$, and $M$ are computed as shown in Table 4.

### TABLE 3. Linguistic assessment influence matrix.

|        | $EA$ (kJ) | $PCF$ (kN) | $M$ (kg) |
|--------|-----------|------------|---------|
| $EA$ (kJ) | 0         | VH         | L       |
| $PCF$ (kN) | VH        | 0          | L       |
| $M$ (kg)   | M         | L          | 0       |

### TABLE 4. The weight vector of the $EA$, $PCF$ And $M$.

|        | $EA$ (kJ) | $PCF$ (kN) | $M$ (kg) |
|--------|-----------|------------|---------|
| Weight | 0.4005    | 0.3853     | 0.2142  |

Based on Table 4, the crashworthiness factor $EA$ occupies the most significant position in the decision-making process. Besides, $PCF$ has about the same weight as $EA$, and the weight of $M$ has a minor proportion in comparison.

### C. EVALUATION AND DECISION

Following the detailed steps of the TODIM method, the final sort of six alternatives can be computed, and the optimal one can be obtained as follows: 1) the decision matrix of six alternatives can be constructed based on the simulation results, including $EA$, $PCF$, and $M$ as shown in Table 1; 2) the normalized decision matrix and the weighted matrix can be calculated combined with the weight of each crashworthiness factor as shown in Table 4 ($PCF$ and $M$ are the set of cost factors; $EA$ is the set of benefit factors); 3) the relative dominance under each indicator can be obtained through Eq. (12); 4) the overall dominance of each alternative is calculated through Eqs. (13) and (14); 5) the comprehensive ranking values that are $\xi_i$, of each alternative can be computed based on Eq. (15), and the optimal one can be obtained as shown in Table 5.

For the result of Table 5, the final rank of six structures with different cross-section configurations can be calculated, i.e., alternative 1 (1.0000) > alternative 2 (0.9948) > alternative 3 (0.8134) > alternative 4 (0.6214) > alternative 5 (0.3087) > alternative 6 (0.0000). That is, with the increase of the floor plate of horsetail-bionic thin-walled EAS, the overall performance is better. Thus, the optimal alternative of six structures is alternative 1, which is the horsetail-bionic thin-walled EAS with six-floor plates.

### D. ANALYSIS AND DISCUSSION

To test the reliability of TODIM results, GRA and TOPSIS methods are used for method comparison analysis [1], [38]. The results and final rank of three methods is shown in Table 6 and Fig. 9.

According to the result of Table 6 and Fig. 9, the conclusions can be drawn that the results of the three method show that alternative 1 is best in method TODIM and GRA, and rank second in TOPSIS. By comparing the results, it can be found alternative 3 to 6 have the same rank and the top two alternatives are 1 and 2. The similar results of the three methods indicate that the results of TODIM are reliable.

In addition, 16 schemes are designed for sensitivity analysis to investigate the relation of the final rank and the weight vector, with different weight vectors of each objective as shown in Table 7. The weight vector of 16 schemes and the final rank is obtained as shown in Table 7 and figured in Fig. 10.

According to the result of Table 7 and Fig. 10, the conclusions can be drawn as follows:

1) the result of each alternative’s final rank has a significant relationship with the weight vector of objectives, and the alternative 1 and alternative 2 have the higher score, that is the optimal one, in 16 schemes of sensitive analysis;

2) obtaining a trustworthy weight vector of the crashworthiness factors, including $EA$, $PCF$, and $M$, according to the requirements of engineering background, is a critical step in the decision-making process and has an important impact on the result of the final rank;
TABLE 5. Ranking of each alternative.

| Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 | Alternative 6 |
|---------------|---------------|---------------|---------------|---------------|---------------|
| $\xi_i$       | 1.0000        | 0.9948        | 0.8134        | 0.6214        | 0.3087        |
| Rank          | 1             | 2             | 3             | 4             | 5             |

TABLE 6. Methods comparison.

| Method | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 | Alternative 6 |
|--------|---------------|---------------|---------------|---------------|---------------|---------------|
| TODIM  | 1             | 2             | 3             | 4             | 5             | 6             |
| GRA    | 1             | 2             | 3             | 4             | 5             | 6             |
| TOPSIS | 2             | 1             | 3             | 4             | 5             | 6             |

TABLE 7. Sensitive analysis.

| No. | $w_1$ | $w_2$ | $w_3$ | Alt.1 | Alt.2 | Alt.3 | Alt.4 | Alt.5 | Alt.6 | Rank       |
|-----|-------|-------|-------|-------|-------|-------|-------|-------|-------|------------|
| 1   | 0.33  | 0.33  | 0.33  | 0.9703| 1.0000| 0.8219| 0.6390| 0.3142| 0.3142| 2>1>3>4>5>6|
| 2   | 0.50  | 0.25  | 0.25  | 1.0000| 0.9718| 0.7903| 0.5972| 0.2921| 0.0000| 1>2>3>4>5>6|
| 3   | 0.25  | 0.50  | 0.25  | 0.9245| 1.0000| 0.8320| 0.6601| 0.3322| 0.0000| 2>1>3>4>5>6|
| 4   | 0.25  | 0.25  | 0.50  | 0.9237| 1.0000| 0.8300| 0.6602| 0.3216| 0.0000| 2>1>3>4>5>6|
| 5   | 0.60  | 0.20  | 0.20  | 1.0000| 0.9524| 0.7724| 0.5777| 0.2825| 0.0000| 1>2>3>4>5>6|
| 6   | 0.20  | 0.60  | 0.20  | 0.8913| 1.0000| 0.8407| 0.6764| 0.3460| 0.0000| 2>1>3>4>5>6|
| 7   | 0.20  | 0.20  | 0.60  | 0.8901| 1.0000| 0.8374| 0.6765| 0.3286| 0.0000| 2>1>3>4>5>6|
| 8   | 0.70  | 0.15  | 0.15  | 1.0000| 0.9375| 0.7592| 0.5629| 0.2755| 0.0000| 1>2>3>4>5>6|
| 9   | 0.15  | 0.70  | 0.15  | 0.8490| 1.0000| 0.8526| 0.6980| 0.3640| 0.0000| 2>3>1>4>5>6|
| 10  | 0.15  | 0.15  | 0.70  | 0.8472| 1.0000| 0.8477| 0.6981| 0.3384| 0.0000| 2>3>1>4>5>6|
| 11  | 0.80  | 0.10  | 0.10  | 1.0000| 0.9245| 0.7480| 0.5505| 0.2697| 0.0000| 1>2>3>4>5>6|
| 12  | 0.10  | 0.80  | 0.10  | 0.7881| 1.0000| 0.8705| 0.7297| 0.3902| 0.0000| 2>3>1>4>5>6|
| 13  | 0.10  | 0.10  | 0.80  | 0.7856| 1.0000| 0.8632| 0.7299| 0.3535| 0.0000| 2>3>1>4>5>6|
| 14  | 0.90  | 0.05  | 0.05  | 1.0000| 0.9111| 0.7364| 0.5372| 0.2640| 0.0000| 1>2>3>4>5>6|
| 15  | 0.05  | 0.90  | 0.05  | 0.6795| 1.0000| 0.9031| 0.7871| 0.4371| 0.0000| 2>3>4>1>5>6|
| 16  | 0.05  | 0.05  | 0.90  | 0.6756| 1.0000| 0.8914| 0.7870| 0.3809| 0.0000| 2>3>4>1>5>6|

FIGURE 10. The decision result of each scheme. (Axial coordinate axis represents the value of $\xi_i$. Outer-most coordinate axis represents the number of schemes).

3) for horsetail-bionic thin-walled EAS, as the number of floor plates increases, the overall performance of $\xi_i$ decreases under the same collision condition.

V. CONCLUSION

Demand is increasing for lightweight structures with high energy absorption capacity for energy absorption application in an array of engineering fields such as aerospace, transportation, nuclear reactors, and civil engineering. This study constructs the finite element model of the horsetail-bionic thin-walled EASs, which is inspired by horsetails’ structural characteristics. An existing train is taken as an empirical case, the crashworthiness, e.g., $EA$ and $PCF$, of six structures with different cross-section configurations are analyzed under the condition of a train collision. Besides, a hybrid decision-making methodology that combines fuzzy DEMATEL and TODIM is proposed, which is proved an effective decision support tool. The result shows the overall performance of horsetail-bionic thin-walled EAS with six-floor plates is the best. The methods comparison is carried out to text the reliability of the results. The comparison result is almost identical, which means the result is reliability. To assess the robustness of monitoring results, a sensitivity analysis is carried out. The results show as the number of floor plates increases, the overall performance of $\xi_i$ decreases. This study provides an effective decision support tool for crashworthiness.
evaluation or structural feature selection of thin-walled structures.

This study effectively fills the gap in the selection of bionic thin-walled structures and can provide a reference for the development of congeneric researches. However, there remain some issues that need to be addressed. In future research, our works will focus on the following: 1) apply advanced decision-making methods to select optimal alternative require more efforts [39], [40]; 2) by noting that the raw data have uncertain and imprecise features, integrate into native require more efforts [39], [40]; 3) explore the influence of different new materials, e.g., biological fiber composites and carbon fiber reinforced composites, on the synthetic performance of energy-absorb structures [43], [44].

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