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Original Article

Modeling of Some Important Mechanical Properties of Barley Straw using Fuzzy Logic

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Abstract

A fuzzy logic model was used to determine the optimum shearing and bending stress of barley straws. The input parameters of the fuzzy model were stem moisture content, internode position and cutting blade loading rate. In order to write the fuzzy rules for the first linguistic variable, stem moisture content, four membership functions (very low, low, medium and high), were defined. Three membership functions (low, middle and high) were considered for the second linguistic variable, stem internode position. In the case of the third linguistic variable, cutting blade loading rate, three membership functions (low, medium and high) were assigned. Three membership functions were also assigned to the two outputs of the fuzzy system, stem shearing stress and bending stress, including low, middle and high. In order to validate the fuzzy model, the mechanical properties of barley straws obtained through preliminary experimental tests were compared with those values acquired using the fuzzy logic rules. The results showed that the model accuracy to estimate the shearing stress of barley straws was 71.4%, 97.1% and 88.9%, respectively in high, middle and low ranges of shearing energy. In the case of bending stress and in high, middle and low ranges, the model accuracy was 92.3%, 95.3% and 75%, respectively.

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Keywords: Fuzzy logic, Model, Barley straw, Shear stress, bending stress

1. Introduction

Intelligent systems based on the fuzzy logic are often used in sorting processes for detecting defects in biological sciences. Fuzzy logic can improve grading processes by using fuzzy sets to define the degrees of overlap. Moreover, application of the “if-then” logics can improve the interpretation and explanation the results and provide a widespread view on the construction of decision process [1]. Zadeh [2] introduced the concept of fuzzy sets as a means for describing complex systems without the requirements for precision. He proclaimed a principle called the “principle of incompatibility”, which states that complexity and precision are incompatible due to the inability of the human mind to comprehend complex systems in a detailed manner. By reducing the need for precision it is possible to more easily express known qualitative relationships about complex systems [3]. He noted that this method for dealing with uncertainty would have particular applicability in soft systems such as psychology, sociology, and economics. Fuzzy logic may also be useful for descriptive systems, those that fall somewhere between hard systems and soft systems, such as biology and agriculture. Fuzzy logic approaches provide a suitable framework for modeling these systems due to their ability to handle “fragmentary, uncertain, qualitative and blended knowledge typically available for biological systems” [4]. Verma [5] developed a fuzzy decision support system (DSS) to aid decisions related to quality sorting of tomatoes. Six fuzzy models were developed and linked to develop the DSS. The outputs of fuzzy DSS predicting quality and the day of the highest quality was very accurate when compared with the data provided by an expert. Some other examples of reported fuzzy logic applications includes a model to predict the effects of multiple stresses on tree growth [6], organizing bioengineering knowledge in fuzzy...
models that can be used for prediction [7, 8], predicting right soil moisture for land preparation [9], feeding strategies on large dairy farms [10], and grading beef quality [11]. Based on the growing evidence from the literature showing successful use of fuzzy logic for modeling, DSS and controls, it appears that applications to biological and agricultural systems are inevitable.

In many agricultural machines, a knife is used to cut plant material and therefore the cutting force must be supported. Often cutting is accomplished by shearing the material between a moving knife and a stationary countershear which is called counter-edge cutting (as used in a combine harvester). In counter-edge cutting, the support force can be provided entirely by the countershear. Sometimes, there is no countershear (as used in flail mowers and rotary mowers), therefore the support force must be provided entirely by the plant itself through the bending strength of the stem below the cut and the inertia of the plant above the cut. The resulting cut is called impact cut, inertia cut, or free cut. As clearance with a countershear increases, the plant strength and inertia come increasingly into play; thus, impact cutting is similar to countershear cutting with very large clearance. Impact cutting is usually used for forage harvesting, while counter-edge cutting is used for cereal harvesting (like barley) as well as forage harvesting. Proper equipment design in order to accomplish the cutting, will maintain the quality of the harvested product [12]. If the product harvesting machines equipped with advanced and precise instruments such as automatic control systems, the speed of machine adjustments versus the sudden changes in the crop conditions in the field could be responded remarkably faster as compared with hand-harvesting. In order to apply an automatic control system on an agricultural machine, first, we need to have the crop properties and then an intermediate software program to make a relation between the human expert knowledge and machine components.

The objective of this study was to model the mechanical properties of barley straw based on the crop harvesting conditions using fuzzy logic. The results of this study may be helpful to design the control systems for the crop harvesting machines such as combines and mowers.

2. Materials and methods
2.1. Preliminary Experimental Tests
2.1.1. Samples preparation
The barley stems (cv. Nosrat) used for the present study were from one of the prevalent varieties of barley in Iran and were obtained from the agronomy farm of the Seed and Seedling Research Institute, Karaj, Iran. The stems were collected at harvest season and their internodes were separated according to their position down from the ear [13]. Leaf blades and sheaths were removed prior to any treatment or measurement. To determine the average moisture content of the barley stems, the specimens were weighed and oven-dried at 103°C for 24 h and then reweighed [14]. The initial moisture content of the specimens was 10.8% (w.b.). To obtain higher moisture levels, samples were rewetted by adding a precalculated mass of water. The rewetted samples were then transferred to separate plastic bags and the bags sealed tightly. The samples were kept at 5°C in a refrigerator for a week to ensure the moisture to be distributed uniformly throughout the samples. The experiments were conducted at four moisture levels of 10.8, 14.3, 18.5 and 22.5% (w.b.). Three internodes of the barley stems, namely, first, second and third internodes, were studied in this research (Fig.1). The fourth and lowest stem internodes from the ear were not considered because these internodes are usually left on the field [15].

2.1.2. Experimental procedure
The shearing stress of barley straw were assessed using a shearing test similar to those described by İnce et al. [16] and Nazari Galedar et al. [17]. The measurements were made using a proprietary tension/compression testing machine (Instron Universal Testing Machine /SMT-5, SANTAM Company, Tehran, Iran). The shear stress was measured in double shear using a shear box (Fig.2a) consisting essentially of two fixed parallel hardened steel plates 6 mm apart, between which a third plate can slide freely in a close sliding fit. A series of holes with diameters ranging from 1.5 to 5 mm were drilled through the plates to accommodate internodes of differing diameters. Shear force was applied to the straw specimens by mounting the shear box in the tension/compression testing machine. The sliding plate was loaded at rates of 5, 10 and mm/min and, as for the shear test, the applied force was measured by a strain-gauge load cell and a force-time record obtained up to the specimen failure.
The shear failure stress (or ultimate shear strength), $\tau_s$, of the specimen was calculated from [15]:

$$\tau_s = \frac{F_s}{2A}$$  \hspace{1cm} (1)

Where $\tau_s$ is the shear stress (MPa), $F_s$ is the shear force at failure (N), and $A$ is the wall area of the specimen at the failure cross-section ($\text{mm}^2$).

To determine the maximum bending stress, the specimens were arranged with the major axis of the cross-section in the horizontal plane and placed on two rounded metal supports 50 mm apart and then loaded midway between the supports with a blade driven by the movable supports (Fig.2b). The loading rates were 5, 10 and 15 mm/min and the applied force was measured by a strain-gauge load cell and a force-time record obtained up to the failure of the specimen. Most specimens were slightly elliptical in cross-section and second moment of area in bending about a major axis ($I_b$) was calculated as [15]:

$$I_b = \frac{n}{2}[a^2b^3 - (a-t)(b-t)^3]$$  \hspace{1cm} (2)

Where $I_b$ is the second moment of area ($\text{mm}^4$), $a$ is the semi-major axis of the cross-section (mm), $b$ is the semi-minor axis of the cross-section (mm) and $t$ is the mean wall thickness (mm).

The maximum bending stress, $\sigma_b$, is defined by [18]:

$$\sigma_b = \frac{F_bal}{4I_b}$$  \hspace{1cm} (3)

Where $\sigma_b$ is the bending stress (MPa), $F_b$ is the bending force (N), $l$ is the distance between the two metal supports (mm), $a$ is the semi-major axis of the cross-section (mm) and $I_b$ is the second moment of area ($\text{mm}^4$).

2.1.3. Experimental design and statistical analysis

This study was planned as a completely randomized block design. The mechanical properties of barley straw were determined with five and ten replications in each treatment of the stems, respectively. Experimental data were analysed using analysis of variance (ANOVA) and the means were compared at the 1% and 5% levels of significance using the Duncan’s multiple range tests in SPSS software (vers. 13, SPSS, Inc., Chicago, IL, USA).

2.2. Fuzzy modeling

2.2.1. Model preparation

Fuzzy logic starts with the concept of fuzzy set. A fuzzy set is defined as a system without certain member that has a clear boundary. The fuzzy set can include all of the elements of the universe of discourse only by one relative degree of membership [2]. In other words, a fuzzy set is defined as a set of ordered pairs in the following form:

$$D = \{ (x, \mu_D(x)) | x \in X, \mu_D(x) \in [0,1] \}$$  \hspace{1cm} (4)

Where $x$ is a member of the $X$, that is to say the universe of discourse, and $D$ is a fuzzy set in the $X$. In Eq. (4), $\mu_D(x)$ is the membership function of $D$ which indicates the degree and/or order in which each $x$ element of $X$ belongs to $D$. This definition assigns a natural number $(\mu_D(x))$ to each $x$ element of $D$ in $[0,1]$ interval. The higher values of $\mu_D(x)$ indicates the higher degrees of membership. The number of fuzzy rules which are necessary to develop a fuzzy control system is directly proportional to the number of each experimental factor, e.g. cutting height [19].

The membership function (MF) is defined as a graphical representation of the magnitude of participation of each input. It associates a weighting with each of the inputs that are processed, define functional overlap between inputs, and...
ultimately determines an output response. The rules use the input membership values as weighting factors to determine their influence on the fuzzy output sets of the final output conclusion. Once the functions are inferred, scaled, and combined, they are defuzzified into a crisp output which drives the system. There are different membership functions associated with each input and output response. Triangular membership function is common, but bell, trapezoidal, haversine and, exponential types have also been used. More complex functions are possible but require greater computing overhead to implement. Triangular and trapezoidal functions are simple and most frequently used in fuzzy sets. In this study, the triangular membership function was evaluated. A triangular membership function is defined as a function having three points in the variation range of a parameter (Fig.3). In the case of a trapezoidal membership function four points are needed. The triangular membership function is mathematically defined as the following equation [2]:

\[
f(x; a, b, c) = \begin{cases} 
0, & x < a \\
\frac{x - a}{b - a}, & a \leq x < b \\
\frac{c - x}{c - b}, & b \leq x < c \\
0, & c \leq x
\end{cases}
\]  

(5)

Equation (5) can be written in the compact form:

\[
f(x; a, b, c) = \max \left( \min \left( \frac{x - a}{b - a}, \frac{c - x}{c - b} \right), 0 \right)
\]

(6)

Where, \( x \) is input vector, and \( a, b, c \) are numbers which are obtained by measurements.

2.2.2. Fuzzy classification

Fuzzy classifiers are one application of fuzzy theory. Expert knowledge is used and can be expressed in a very natural way using linguistic variables, which are described by fuzzy sets. Then the expert knowledge for linguistic variables can be formulated as a rule base. Linguistic rules describing the control system consist of two parts; an antecedent block (between the IF and THEN) and a consequent block (following THEN). In fuzzy logic, fuzzy sets and fuzzy operators are acts and actuators. If fact, the “if-then” rules formulate the necessary conditions for fuzzy logic to decide and grading. A single fuzzy logic is written as below:

\[\text{IF } x \text{ is } A, \text{THEN } y \text{ is } B\]  

(7)

Where \( A \) and \( B \) are defined linguistic variables for \( x \) and \( y \) variables by fuzzy sets in the range of \( X \) and \( Y \), the universes of discourse. Fuzzy logic rules could also be written in combined form by use of AND operator:

\[R_i: \text{IF } x_i \text{ is } A_i \text{ AND } y_i \text{ is } B_i \text{ THEN } Z_i \text{ is } C_i\]  

(8)

Where \( A_i \) and \( B_i \) are fuzzy sets for \( x_i \) and \( y_i \) inputs which assign linguistic variables such as low, middle and high and \( n \) is the number of rules [20]. In the current study, \( C_i \) could include the linguistic variables to determine the level of output factors.

2.2.3. Defuzzification process

Defuzzification is the process of producing a quantifiable result in fuzzy logic, given fuzzy sets and corresponding membership degrees. It is typically needed in fuzzy control systems. These will have a number of rules that transform a number of variables into a fuzzy result, that is, the result is described in terms of membership in fuzzy sets. In other words, defuzzification is interpreting the membership degrees of the fuzzy sets into a specific decision or real value. By use a defuzzifier, the output variable converts to a real value. There are many different methods of defuzzification such as center of gravity (COG), mean of maximum (MOM), center of maximum (COM), and first of maximum (FOM) [21]. In this study, the center of gravity (COG) approach was used for conducting the fuzzy processes.

After measurement the mechanical strength of barley straws at different levels of experimental evaluated factors, the fuzzy model was developed. The three evaluated factors in this study (stem moisture content, internode position and loading rate) were considered as the three input linguistic variables to the fuzzy logic model. These parameters were initially in the form of real values. First, these crisps were converted to fuzzy values by the fuzzy system. The fuzzy logics were applied using the Mamdani product (minimum) interface engine [20]. Then the fuzzy logics were processed. Finally, the fuzzy system defuzzified the results using center of maximum (COM) defuzzifier and provided a real value indicating the level of stem shear strength.

3. Results and discussion

3.1. Shearing and Bending Stresses of Straws

The mean values of shear strength of barley straw at different moisture contents, internode positions and loading rates are presented in Table 1. The shear strength increased towards the third internode position and the first internode had significantly lower values \((P<0.01)\) than the other two internodes. By Duncan’s multiple range tests, the shear strength was found to be significantly lower \((P<0.05)\) for the lowest moisture content \((10.8\% \text{ w.b.})\) than for the other three moisture contents, which may be due to the driest straw being more brittle. For the three internode positions, the values of shearing stress initially increased with increasing loading rate from 5 to 10 mm/min and then further increase in loading rate from 10 to 15 mm/min caused the shear stress to decrease. Based on the statistical analysis, the effects of stem moisture content, internode position and loading rate on the shearing stress were significant at the 1% probability level.

As shown in Table 1, the bending stress decreased with an increase in moisture content for all internode positions, indicating a reduction in the brittleness of the stem. The mean values of the bending stress ranged from 5.01 to 9.17 MPa. The bending stress increased towards the upper internode position.
Figure 4. Overall form of fuzzy model for estimating shear and bending stresses of barley straw

Figure 5. The membership functions used to give a description range of: a) Stem moisture content, b) Stem internode position, c) Cutting blade loading rate, and d) Stem bending stress
rate from 5 to 10 mm/min, the bending stress increased initially and then, further increase in loading rate from 10 to 15 mm/min caused a decrease in the value of bending stress. Based on the results obtained through analysis of variance, it was revealed that the effects of stem moisture content, internode position and loading rate on the bending stress were all significant at the 1% significance level.

3.2. Fuzzy model establishment

The process of the fuzzy logic model establishment in MATLAB software is shown in Fig 4 and Fig 5. In Fig 4, the overall form of the fuzzy model in MATLAB software is illustrated. In order to write the fuzzy rules for the first linguistic variable, stem moisture content, four membership functions namely, very low [5 12], low [11 16], medium [15 20], and high [19 25], all in terms of wet basis percentage were defined (Fig 5a). In the case of second linguistic variable, stem internode position, three membership functions including low [0 30], middle [25 70] and high [65 120], all in cm were defined (Fig 5b). For the third linguistic variable, cutting blade loading rate, three membership functions including low [0 6], medium [5 11] and high [10 16], all in terms of mm/min were assigned (Fig 5c). Three membership functions were also assigned to the outputs of the fuzzy system, shearing stress and bending stress. The three levels assigned to the shearing and bending stresses were low [0 4], middle [3 7], and high [6 10] in terms of MPa (Fig 5d). The ranges for all of the input and output variables were determined by an expert based on the values obtained through the preliminary experimental tests (Table 1). The determination process of fuzzy rules for the mechanical properties of the barley straw in MATLAB software is shown in Fig 6. Combining the assigned membership functions and based on the results of the experimental measurements, 36 fuzzy rules were totally obtained using AND operator in fuzzy sets. The rules are listed in Table 2. These rules were used to establish a relationship between the input and output variables.

3.3. Fuzzy model assessment

Fig 7. shows the assessment of the applied rules in the fuzzy model in MATLAB software. The figure indicate the output of the fuzzy model considering the stem moisture content, internode position and loading rate at very low, middle and medium ranges, respectively. In such a condition, the model estimation for shearing and bending stresses is placed in medium and high ranges, respectively. This is consistent with primary definitions of fuzzy rules in (See rule No. 5 in the Table 2). In Fig. 8 a sample surface viewer of fuzzy system considering stem moisture content and loading rate as input variables is given.
## Table 1. Shearing characteristics of barley straw at different moisture contents, loading rates and internode positions obtained through preliminary experimental test

<table>
<thead>
<tr>
<th>Moisture Content (%w.b.)</th>
<th>Loading rate (mm/min)</th>
<th>Internode position*</th>
<th>Bending stress (MPa)</th>
<th>Shearing stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Upper</td>
<td>Middle</td>
<td>Lower</td>
</tr>
<tr>
<td>10.8</td>
<td>5</td>
<td>9.17 (1.02)</td>
<td>6.88 (0.63)</td>
<td>6.24 (1.20)</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>8.55 (1.10)</td>
<td>8.39 (0.75)</td>
<td>8.14 (1.37)</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>7.64 (0.87)</td>
<td>7.01 (0.77)</td>
<td>6.94 (1.07)</td>
</tr>
<tr>
<td>14.3</td>
<td>5</td>
<td>9.03 (1.24)</td>
<td>6.52 (0.98)</td>
<td>5.95 (0.71)</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>7.73 (1.63)</td>
<td>7.29 (1.25)</td>
<td>7.23 (0.79)</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>7.19 (1.19)</td>
<td>6.93 (1.11)</td>
<td>6.42 (0.85)</td>
</tr>
<tr>
<td>18.5</td>
<td>5</td>
<td>6.91 (0.73)</td>
<td>6.09 (0.47)</td>
<td>5.65 (0.36)</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>7.28 (0.68)</td>
<td>7.11 (1.27)</td>
<td>6.79 (0.62)</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>7.02 (0.92)</td>
<td>6.72 (1.03)</td>
<td>6.21 (0.55)</td>
</tr>
<tr>
<td>22.5</td>
<td>5</td>
<td>6.73 (1.07)</td>
<td>5.89 (0.91)</td>
<td>5.01 (0.73)</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>7.08 (0.71)</td>
<td>6.56 (0.83)</td>
<td>6.30 (0.84)</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>6.88 (0.88)</td>
<td>6.15 (0.84)</td>
<td>5.93 (0.49)</td>
</tr>
</tbody>
</table>

* Figures in parentheses are standard deviation

## Table 2. Fuzzy rules obtained through AND operator in the fuzzy sets

1. If (Moisture is Very Low) and (Internode is Lower) and (Loading Rate is Low) then (Shearing Stress is Low) (Bending Stress is Medium)
2. If (Moisture is Very Low) and (Internode is Lower) and (Loading Rate is Medium) then (Shearing Stress is Medium) (Bending Stress is High)
3. If (Moisture is Very Low) and (Internode is Lower) and (Loading Rate is High) then (Shearing Stress is Low) (Bending Stress is Medium)
4. If (Moisture is Very Low) and (Internode is Middle) and (Loading Rate is Low) then (Shearing Stress is Low) (Bending Stress is Medium)
5. If (Moisture is Very Low) and (Internode is Middle) and (Loading Rate is Medium) then (Shearing Stress is Medium) (Bending Stress is High)
6. If (Moisture is Very Low) and (Internode is Middle) and (Loading Rate is High) then (Shearing Stress is Low) (Bending Stress is High)
7. If (Moisture is Very Low) and (Internode is Upper) and (Loading Rate is Low) then (Shearing Stress is Low) (Bending Stress is High)
8. If (Moisture is Very Low) and (Internode is Upper) and (Loading Rate is Medium) then (Shearing Stress is Medium) (Bending Stress is Medium)
9. If (Moisture is Very Low) and (Internode is Upper) and (Loading Rate is High) then (Shearing Stress is Low) (Bending Stress is High)
10. If (Moisture is Low) and (Internode is Lower) and (Loading Rate is Low) then (Shearing Stress is Medium) (Bending Stress is Medium)
11. If (Moisture is Low) and (Internode is Lower) and (Loading Rate is Medium) then (Shearing Stress is Medium) (Bending Stress is High)
12. If (Moisture is Low) and (Internode is Lower) and (Loading Rate is High) then (Shearing Stress is Medium) (Bending Stress is High)
13. If (Moisture is Low) and (Internode is Middle) and (Loading Rate is Low) then (Shearing Stress is Medium) (Bending Stress is High)
14. If (Moisture is Low) and (Internode is Middle) and (Loading Rate is Medium) then (Shearing Stress is Medium) (Bending Stress is High)
15. If (Moisture is Low) and (Internode is Middle) and (Loading Rate is High) then (Shearing Stress is Medium) (Bending Stress is High)
16. If (Moisture is Low) and (Internode is Upper) and (Loading Rate is Low) then (Shearing Stress is Medium) (Bending Stress is High)
17. If (Moisture is Low) and (Internode is Upper) and (Loading Rate is Medium) then (Shearing Stress is Medium) (Bending Stress is High)
18. If (Moisture is Low) and (Internode is Upper) and (Loading Rate is High) then (Shearing Stress is Medium) (Bending Stress is High)
19. If (Moisture is Medium) and (Internode is Lower) and (Loading Rate is Low) then (Shearing Stress is Medium) (Bending Stress is Medium)
20. If (Moisture is Medium) and (Internode is Lower) and (Loading Rate is Medium) then (Shearing Stress is Medium) (Bending Stress is High)
21. If (Moisture is Medium) and (Internode is Lower) and (Loading Rate is High) then (Shearing Stress is Medium) (Bending Stress is Medium)
22. If (Moisture is Medium) and (Internode is Middle) and (Loading Rate is Low) then (Shearing Stress is Medium) (Bending Stress is Medium)
23. If (Moisture is Medium) and (Internode is Middle) and (Loading Rate is Medium) then (Shearing Stress is Medium) (Bending Stress is High)
24. If (Moisture is Medium) and (Internode is Middle) and (Loading Rate is High) then (Shearing Stress is Medium) (Bending Stress is High)
25. If (Moisture is Medium) and (Internode is Upper) and (Loading Rate is Low) then (Shearing Stress is Medium) (Bending Stress is High)
26. If (Moisture is Medium) and (Internode is Upper) and (Loading Rate is Medium) then (Shearing Stress is Medium) (Bending Stress is Medium)
27. If (Moisture is Medium) and (Internode is Upper) and (Loading Rate is High) then (Shearing Stress is Medium) (Bending Stress is Medium)
28. If (Moisture is High) and (Internode is Lower) and (Loading Rate is Low) then (Shearing Stress is Medium) (Bending Stress is Medium)
29. If (Moisture is High) and (Internode is Lower) and (Loading Rate is Medium) then (Shearing Stress is Medium) (Bending Stress is Medium)
30. If (Moisture is High) and (Internode is Lower) and (Loading Rate is High) then (Shearing Stress is Medium) (Bending Stress is Medium)
31. If (Moisture is High) and (Internode is Middle) and (Loading Rate is Low) then (Shearing Stress is Medium) (Bending Stress is Medium)
32. If (Moisture is High) and (Internode is Middle) and (Loading Rate is Medium) then (Shearing Stress is Medium) (Bending Stress is Medium)
33. If (Moisture is High) and (Internode is Middle) and (Loading Rate is High) then (Shearing Stress is Medium) (Bending Stress is Medium)
34. If (Moisture is High) and (Internode is Upper) and (Loading Rate is Low) then (Shearing Stress is Medium) (Bending Stress is Medium)
35. If (Moisture is High) and (Internode is Upper) and (Loading Rate is Medium) then (Shearing Stress is Medium) (Bending Stress is Medium)
36. If (Moisture is High) and (Internode is Upper) and (Loading Rate is High) then (Shearing Stress is Medium) (Bending Stress is Medium)
After establishment of the fuzzy sets and fuzzy rules determination, in order to validate the fuzzy model, the mechanical properties of barley straws obtained through the preliminary experimental tests were compared with those values acquired by the fuzzy rules. The results of the model assessment by an expert person are given in Table 3. It was revealed that the fuzzy model used in this study had an acceptable prediction ability to determine the level of mechanical strength of barley straws. The model accuracy to estimate the shearing stress of barley straws was 71.4%, 97.1% and 88.9%, respectively in high, middle and low ranges of shearing energy. In the case of bending stress and in high, middle and low ranges, the model accuracy was 92.3%, 95.3% and 75%, respectively.

4. Conclusion

This study was planned to develop a model based on fuzzy logic to estimate the shearing and bending strength of barley straws considering the crop harvest conditions. Experimental tests were initially conducted to obtain the real values of shearing stress and bending stress for barley straws in terms of the crop stem moisture content, internode position and cutting blade loading rate. The results showed that the values of shearing stress and bending stress for the barley straw varied from 2.27 to 6.18 MPa and 5.10 to 9.17 MPa, respectively. After measurement the mechanical strength of barley straws at different levels conditions, the fuzzy model was developed. The three evaluated factors in this study (stem moisture content, internode position and loading rate) were considered as the three input linguistic variables to the fuzzy logic model. The fuzzy logics were applied and processed using the Mamdani product (minimum) interface engine. After establishment of the fuzzy sets and fuzzy rules determination, in order to validate the fuzzy model, the shearing stress and bending stress of barley straw obtained through the experimental tests were compared with those values acquired using the fuzzy logic rules. The results showed that the fuzzy model used in this study had an acceptable prediction ability to determine the level of shearing stress and bending stress of barley straws. The model accuracy to estimate the shearing stress of barley straws was 71.4%, 97.1% and 88.9%, respectively in high, middle and low ranges of shearing energy. In the case of bending stress and in high, middle and low ranges, the model accuracy was 92.3%, 95.3% and 75%, respectively.

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