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Robust Design and Tolerance Simulation of Bolt-fastening Axial Force-monitoring Washer using FEM Analysis

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ABSTRACT

When fixing a structure using bolts, it is crucial to apply sufficient bolt axial force. Hence, several methods have been proposed to measure the applied axial force exerted on the bolt. However, these methods are either expensive or complicated. To overcome these problems, we proposed a method to measure the axial force by analyzing the change in shape of the washer. The basic shape of the washer was designed using a commercial software and redesigned into the most robust form according to the change in tolerance while measuring a force of 200 kN. To achieve this, the sensitivity and interaction of each parameter was examined to determine the appropriate parameter values. The adequacy of the final model was verified using the additive model and Monte Carlo method. The result s proved that the proposed model had high reliability and robustness.

1. Introduction

Fastening is very important for structures. Proper fastening can be obtained by applying a proper fastening force, so it is important to control this force. Appropriate measurement methods are needed to ensure proper fastening, but it is not easy to measure the characteristics of fastening in situ. Several studies have been carried out to measure the axial force of a bolt over the years. Ren[1] developed a new type of smart bolt that can measure axial and shear forces simultaneously through embedded fiber bragg grating (FBG) sensors. Yin[2] developed a method to check the axial force using a smart washer equipped with two piezoelectric patches. Yang[3] proposed an attenuation-based diagnostic method to assess fastener integrity by observing the attenuation patterns of the resultant sensor signals. Amenrini[4] developed an integrity index to measure the health state of contact interfaces in composite structures using ultrasonic waves. However, all of these methods have been disadvantages in that they are too expensive or complicated to apply in the field. A direct tension indicator (DTI) is used in axial force-monitoring washers[5]. DTI washers are designed to allow silicone to escape from the washer in proportion to the axial force exerted on it. However, the amount of silicon that escapes is not directly proportional to the axial force, and the measured force has large deviations. Moreover, this product is imported and relatively expensive, so construction costs become high when the washers are used in large steel structures that

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require many fasteners. Furthermore, silicon also causes environmental pollution. To overcome these difficulties, it is necessary to develop an inexpensive washer that can directly monitor the tightening force of a bolt. Like other products, washers also have manufacturing errors that are controlled through their tolerances. The tolerance of each part either linearly or nonlinearly affects the tolerance of the finished washer. The tolerance of some parts has a bigger effect on the tolerance than others. For robust design, the effect of each parameter on the finished washer is first determined, and a combination of parameters that have the smallest effect on the finished washer has to be selected[6]. In this way, a robust washer can be designed where the axial force can be measured visually. The effect of each parameter can be determined by either manufacturing and studying a prototype or through simulations. The design method of changing the design parameters is widely used in the industry[7] and experimental design method is used as a way to reduce the number of experiments[8]. Rout[9] used an experimental design method to simulate the influence of the tolerances of a robot arm, but the effects were determined in the product stage rather than the design stage. Mahmood[10] studied the relationship between process parameters and dimensional accuracy using an experimental design method. The relationship between the manufacturing method and dimensional accuracy was determined for most fused-deposition modeling printers. Goetz[11] proposed a method for evaluating tolerances in the conceptual design phase. This is a method of evaluating the approximate influence using a tolerance graph at the conceptual design stage. However, no study has been conducted on the effect of tolerance deviations on the overall performance in the design phase.

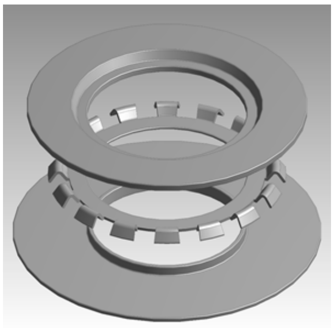
We propose a method of using the deformations of a washer for axial force monitoring. A robust washer was designed with minimal performance changes of the finished product even with variations in the tolerances of each part. The essential function of the washer is to maintain the axial force and prevent loosening. The rigidity of the washer should be high for this purpose, or else the washer will wear out and deform, which reduces the axial force. As a result, the bolt becomes loose, which causes the entire structure to loosen. On the other hand, the deformation of the washer must be large to measure the axial force through its the deformation. Greater deformation makes it easier to visually determine the amount of deformation and its relationship with the axial force. High rigidity and ease of deformation are incompatible with each other. The rigidity must be small to facilitate axial force measurements, but it must also be large to maintain the axial force. This conflicting situation must be solved to monitor the axial force using the washer’s deformation.

2. Design of Bolt Fastening Axial Force Monitoring Washer

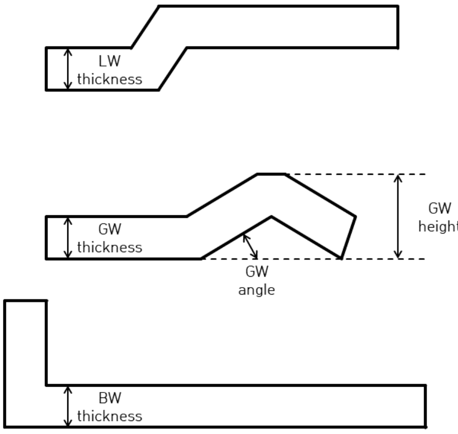
To achieve a robust washer design under varying tolerances, the combination of tolerances of each component that has the least effect on the finished product was selected. However, this combination produces different results than the target value in most cases. To overcome this, it is common to find a proportional factor to adjust to the target value, but it is not easy to do so. In this study, we propose a method to determine the specific control factor to adjust axial force to the target value. Using this method, we show that the axial force can be adjusted to the desired value while maintaining or even increasing the robustness of the design.

The proposed washer was divided into three parts: a load washer (LW) to maintain the rigidity, a gage washer (GW) to measure the axial force, and a bottom washer (BW) (see Fig. 1). The influence of each part’s tolerance was minimized in the design stage. The effect of the component tolerances on those of the finished product was obtained by simulation for different combinations of design parameters.

LW maintains the tightening force of bolts and nuts. It is flattened with a force of 200 kN and maintains its axial force over time. To maintain the axial force, the part must be thick for high rigidity. However, if it is too thick, it is too hard to deform, so the thickness must be properly determined. A GW is use used for visual deformation and is made in a form that resembles spider legs for easy deformation. This component is plastically deformed outwards toward the circumference when an axial force is applied, and the amount of deformation depends on the applied axial force, the LW maintains the tightening force of bolts and nuts. It is flattened with a force of 200 kN and maintains its axial force over time.



(a) Assembly drawing



(b) Cross section of the washer component

Fig. 1 Design of axial force monitoring washer

To maintain the axial force, the part must be thick for high rigidity. However, if it is too thick, it is too hard to deform, so the thickness must be properly determined. A GW is use used for visual deformation and is made in a form that resembles spider legs for easy deformation. This component is plastically deformed outwards toward the circumference when an axial force is applied, and the amount of deformation depends on the applied axial force, the thickness and height of GW, and the initial angle. Therefore, the design parameters of GW are the thickness, height, and initial angle. BW supports both LW and GW while preventing them from interfering with the bolt. The height and thickness are important parameters of BW. In the design of the washer, the bent height inside BW is related to the heights of LW and GW. The initial simulation results showed found that when the bent height of the inner part of BW is low, LW separates upward from BW and causes a large increase in the axial force. Therefore, it is important to determine a proper height for BW.

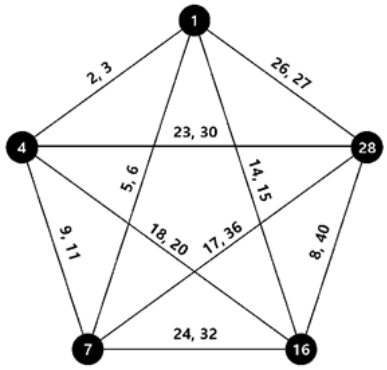


Fig. 2 Linear graph of L81 orthogonal array

3. Initial Washer Design

3.1 Orthogonal array for design and interactions of washer

The commercial software ANSYS Ver. 17.0 was used for the design of the proposed washer. Five important parameters (LW thickness, BW thickness, GW thickness, GW height, GW angle) and 10 interactions of these five important parameters were selected as the design parameters. For optimal design, an orthogonal array table with at least 26 three-level columns is required to achieve the number of parameters, interactions, and error effects. The orthogonal array table that satisfies this condition is only L81 orthogonal array that has 40 three-levels columns[6]. In this case, we could not find an interaction table and graph, so we used Matlab to obtain a linear graph, as shown in Fig. 2. In the Fig. 2, each vertex number refers to a column in which each of the five independent parameters must be placed. The numbers of the straight lines connecting the vertices indicate the columns that must be left empty to obtain the interactions between independent parameters. In accordance with the line graph, major parameters should be assigned to columns 1, 4, 7, 16, and 28, and the columns corresponding to the connection lines should be left empty. Optimum conditions were obtained by conducting 81 simulations according to the line graph and performing an analysis of variance.

3.2 Design parameters range and interactions

Table 1 shows the three-level values of the parameters to be placed in each column to perform simulations using the L81 orthogonal array table. These values were determined so that the washer could measure an axial force of around 200

Table 1 Three levels of important factors

Factor	Levels		
	1	2	3
LW thickness (mm)	0.96	1.20	1.44
GW thickness (mm)	0.40	0.50	0.60
BW thickness (mm)	0.56	0.70	0.84
GW height (mm)	1.20	1.50	1.80
GW angle (°)	45.00	50.00	55.00

kN. A grid-size dependence test was performed as the first step of optimization using simulation. The test was performed to confirm that the results converged as the size of the grid became smaller.

The size of the grid was decreased from 2.5 mm to 0.7 mm in the case of the bolts and nuts, from 1.2 mm to 0.12 mm at intervals of 0.06 mm in the case of LW, from 0.5 mm to 0.14 mm at intervals of 0.02 mm in the case of GW, and from 0.7 mm to 0.25 mm at intervals of 0.025 mm in the case of BW. In all cases, there was almost no difference between the axial force and the deformation length due to the change in the grid size. Therefore, the size of the grid was determined to be the maximum size with the smallest analysis time. However, the grid sizes were selected as 0.3 mm for LW, 0.3 mm for GW, and 0.4 mm for BW to form a mesh of at least two layers and increase the reliability of the results.

Table 2 Analysis of variation (ANOVA) results for axial force including interaction effects

	Degrees of freedom	Sum of squares	Mean square	F
LW thickness	2	17138.4	8569.21	781.74
GW thickness	2	208.6	104.28	9.52
BW thickness	2	11.8	5.87	0.54
GW height	2	27094.5	13547.22	1235.87
GW angle	2	98.2	49.09	4.48
A x B	4	291.6	72.90	6.65
A x C	4	139.3	34.82	3.18
A x D	4	214.7	53.67	4.90
A x E	4	6.1	1.52	0.14
B x C	4	131.0	32.76	2.99
B x D	4	232.58	58.15	5.30
B x E	4	142.7	35.67	3.25
C x D	4	60.5	15.13	1.38
C x E	4	35.41	8.85	0.81
D x E	4	126.67	31.67	2.89
Error	30	328.85	10.96	1.00
Sum	80	46260.8	578.26	-

Table 3 Analysis of variation (ANOVA) results for deformation length including interaction effects

	Degrees of freedom	Sum of squares	Mean square	F
LW thickness	2	0.00	0.00	12.09
GW thickness	2	1.1	0.55	4092.27
BW thickness	2	0.0	0.01	55.48
GW height	2	4.9	2.44	18131.45
GW angle	2	0.3	0.16	1217.21
A x B	4	0.0	0.00	0.41
A x C	4	0.0	0.00	0.71
A x D	4	0.0	0.00	0.34
A x E	4	0.0	0.00	0.22
B x C	4	0.0	0.00	0.23
B x D	4	0.0	0.00	17.94
B x E	4	0.0	0.00	27.38
C x D	4	0.0	0.00	0.56
C x E	4	0.0	0.00	0.03
D x E	4	0.0	0.01	74.99
Error	30	0.0	0.00	1.00
Sum	80	6.4	0.08	-

The axial force and deformation length were analyzed, and the results are shown in Tables 2 and 3. The results show that the F values of the interactions are very small, which confirms that there are almost no interactions. The parameters that have the greatest influence on the axial force are the GW height and the LW thickness, which have the largest F values in Table 2. In Table 3, the parameter that has the greatest effect on the deformation length is the GW height, followed by the GW thickness. Therefore, optimization was performed to maximize the deformation length by adjusting the GW height and thickness and then to match the target axial force with the LW thickness.

3.3 Simulation using reduced parameters

The interaction between the parameters is negligibly small, so only the main effects of the 5 three-level parameters needed to be identified. In this case, the L18 orthogonal array table is sufficient, but an L25 orthogonal array table was used to examine the deformation trends more closely and to determine the optimal values more accurately. The error range should be determined for the simulation of the noise factor caused by the tolerances. The error range is given in Table

5, and an L9 orthogonal array table was used for its analysis. An L18 orthogonal array table is required for the noise analysis of the 5 parameters of 3-level factors. However, since the BW thickness does not affect the axial force and deformation length, it can be analyzed with four parameters, so an L9 orthogonal array table is sufficient. The error level caused by the tolerances was given as 7.36% for all parameters. The simulation results with 5 control parameters and 5 error parameters are shown in Tables 6 and 7. The results show that the GW height and LW thickness have the greatest effect on the axial force, while the GW height and GW thickness have the greatest effect on the deformation length. This is the same result as when interpreting the design including interactions.

Table 4 Five levels of five control parameters

Factor	Levels				
	1	2	3	4	5
LW thickness (mm)	0.96	1.08	1.20	1.32	1.44
GW thickness (mm)	0.40	0.45	0.50	0.55	0.60
BW thickness (mm)	0.56	0.63	0.70	0.77	0.84
GW height (mm)	1.20	1.35	1.50	1.65	1.80
GW angle (°)	45.00	47.50	50.00	52.50	55.00

4. Robust washer design

4.1 Interpretation result

Figs. 3 and 4 show the results of the mean and signal-to-noise ratio (S/N ratio) analysis for each parameter for the axial force and deformation length. Fig. 3(a) shows that the LW thickness and GW height are the most influential factors on the axial force. Fig. 3(b) shows that the GW height is the most influential factor on the S/N ratio. In Fig. 4(a), the factor that most significantly influences the deformation

Table 5 Three levels of four error parameters

Factor	Levels (%)		
	1	2	3
LW thickness	97	100	103
GW thickness	97	100	103
GW height	97	100	103
GW angle	97	100	103

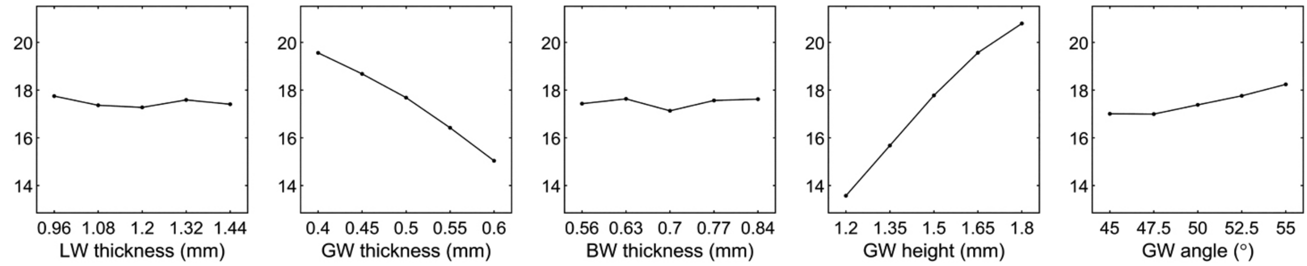
Table 6 ANOVA results for axial force with main effects only

	Levels								
	1	2	3	4	5	Degrees of freedom	Sum of quares	Mean squares	F
LW thickness	178.0	186.4	197.6	205.9	211.2	4	3,737.7	934.41	56.27
GW thickness	199.6	196.2	195.5	194.3	193.6	4	112.0	27.99	1.69
BW thickness	196.2	195.4	193.8	196.3	197.5	4	37.6	9.39	0.57
GW height	170.7	187.0	197.2	208.2	216.0	4	6,377.5	1,594.37	96.01
GW angle	195.1	194.1	199.3	193.5	197.1	4	111.9	27.97	1.68
Error	-	-	-	-	-	4	66.4	16.61	-
Sum	-	-	-	-	-	2	10,443.0	435.12	-

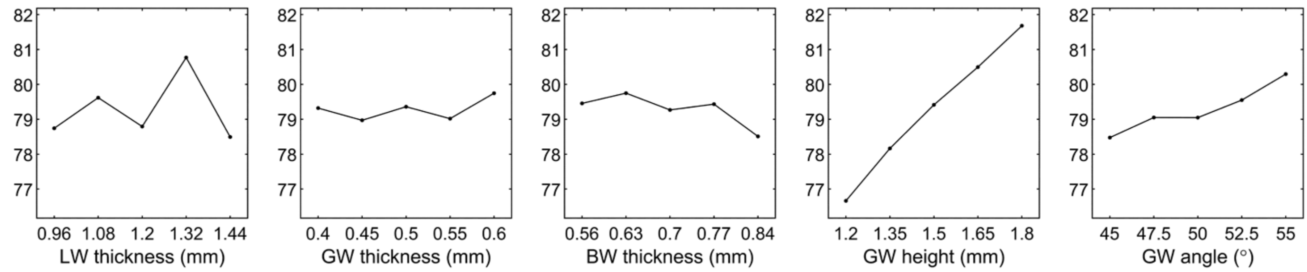
Table 7 ANOVA results for deformation length with main effects only

	Levels								
	1	2	3	4	5	Degrees of freedom	Sum of squares	Mean squares	F
LW thickness	0.894	0.890	0.865	0.894	0.898	4	0.01	0.00	0.91
GW thickness	1.030	0.981	0.874	0.822	0.736	4	0.28	0.07	46.81
BW thickness	0.875	0.882	0.888	0.893	0.904	4	0.00	0.00	0.42
GW height	0.579	0.740	0.889	1.051	1.183	4	1.18	0.29	196.04
GW angle	0.811	0.843	0.889	0.934	0.966	4	0.08	0.02	13.05
Error	-	-	-	-	-	4	0.01	0.00	-
Sum	-	-	-	-	-	24	1.55	0.06	-

length is the GW height, followed by the GW thickness and GW angle. In Fig. 4(b), the factors affecting the S/N ratio of the deformation length are again the GW thickness, GW height, and GW angle. The deformation length and S/N ratio are maximized at the same time when selecting level 1 of the GW thickness (0.4 mm), level 5 of the GW height (1.8 mm), and level 5 of the GW angle (55°) using Fig. 4. The effects of the LW thickness and BW thickness on the deformation length and S/N ratio are not significant, so any level can be selected. This results in a robust system that is the most most insensitive to the noise of the parameters with the maximum deformation length. In Fig. 5, the values with a large S/N ratio of the axial force are level 4 of the LW thickness (1.32 mm), level 1 of the GW thickness (0.4 mm), level 2 of the BW thickness (0.63 mm), level 5 of the GW height (1.8 mm), and level 4 of the GW angle (52.5°). However, the LW thickness is used later to match the target axial force because it has the greatest effects on the axial force and is relatively

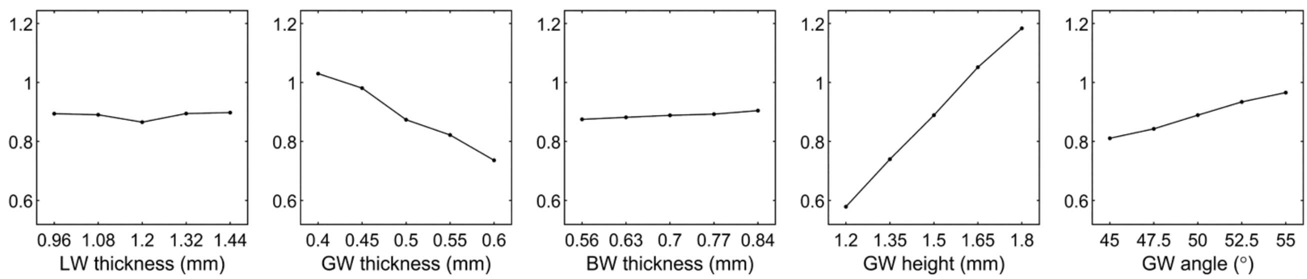


(a) Average value of axial force at each level (kN)

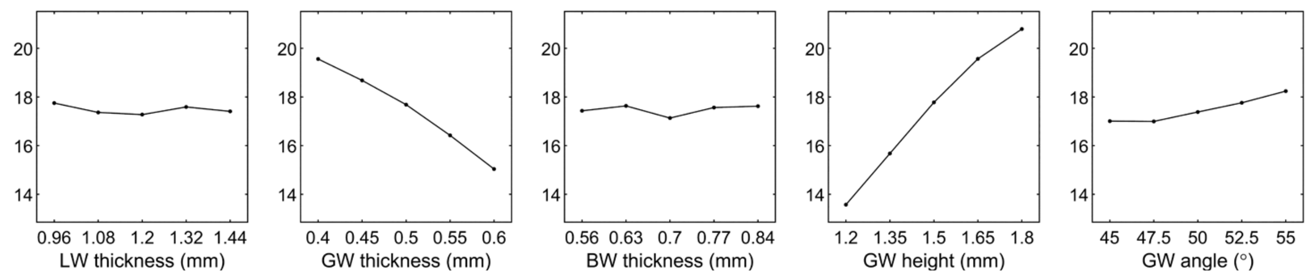


(b) S/N ratio of axial force at each level (kN)

Fig. 3 Average value and S/N ratio of axial force at each level



(a) Average value of deformation length at each level (mm)



(b) S/N ratio of deformation length at each level (mm)

Fig. 4 Average value and S/N ratio of deformation length at each level

insignificant for the S/N ratio.

Next, we determined the parameters that simultaneously maximize the amount of deformation length, its S/N ratio, and the S/N ratio of the axial force. The GW thickness was determined to be level 1 (0.4 mm), which is an ideal level that simultaneously maximizes the S/N ratio of the deformation length while increasing the S/N ratio of the axial force. The BW thickness was determined to be level 2 (0.63 mm) to increase the robustness without affecting the deformation length. The reason for choosing the BW thickness as level 2 is that it does not affect the deformation length while increasing the robustness by improving the S/N ratio of the axial force.

The GW height was determined as level 5 (1.8 mm), which is ideal because it maximizes both the deformation length and the S/N ratios of the axial force and deformation length. When the GW height is level 5, the axial force is increased. The increased axial force can be adjusted by controlling the LW thickness. Since the effects of the difference between the two values is not large, the GW angle can be either level 4 (52.5°) or level 5 (55°). As a result, the optimum conditions for maximum robustness were determined as GW thickness level 1 (0.4 mm), BW thickness level 2 (0.63 mm), GW height level 5 (1.8 mm), and GW angle level 5 (55°). To produce an axial force of 200 kN, the LW thickness was determined to be 1.02 mm, which is between levels 1 and 2.

4.2 Final washer design

Simulations were performed where the GW thickness was level 1 (0.4 mm), the BW thickness was level 2 (0.63 mm), the GW height was level 5 (1.8 mm), the GW angle was level 5 (55°), and the LW thickness was between levels 1 and 2 (1.02 mm). Each parameter value was determined to maximize the deformation and S/N ratio while adjusting the axial force to 200 kN using the LW thickness. The simulation results show that the axial force is 200.05 kN, which is very close to the target of 200 kN. The S/N ratio of the axial force increased by 30.32% from 33.49 to 35.79, which shows that the robustness of the axial force was increased. The deformation length increased greatly by 63.64% from 0.88 mm to 1.44 mm, and the S/N ratio of the deformation length was greatly improved by 69.24% from -1.43 to 3.14. The mean results of all the simulations performed according to the orthogonal array table were an axial force S/N ratio of 33.49, deformation length of 0.88 mm, and deformation S/N ratio of -1.43.

4.3 Prediction of axial force and deformation length using an additive model

Because the interaction was found to be very small, an optimal design was carried out while assuming that all parameters are independent. To determine whether this assumption is correct, it is necessary to compare the optimal design results with those obtained from an additive model[6] of the axial force:

$$\begin{aligned}\text{prediction} = \mu + (m_{LW\_t} - \mu) + (m_{GW\_t} - \mu) + \\ (m_{BW\_t} - \mu) + (m_{GW\_h} - \mu) + (m_{GW\_a} - \mu)\end{aligned} \tag{1}$$

where μ is the mean value, m_{LW_t} is the effect of the LW thickness, m_{GW_t} is the effect of the GW thickness, m_{BW_t} is the effect of the BW thickness, m_{GW_h} is the effect of the GW height, and m_{GW_a} is the effect of the GW angle. The optimum conditions from section 4.2 (1.02-mm LW thickness, 0.4-mm GW thickness, 0.63-mm BW thickness, 1.8-mm GW height, and 55° GW angle) were inserted into Eq. (1) to calculate the axial force and its variation. The corresponding axial forces are shown in Table 6.

The resultant axial force was 207.06 kN, the variation was 15.79 kN, and the 95% confidence interval was 207.056 ± 7.95 kN. The axial force of 200.05 kN obtained with optimum conditions is within the 95% confidence interval obtained by the additive model. As a result, the additive model can be used to predict the axial force instead of the time-consuming simulation model. The small differences between the additive model and the simulation model are caused by small interactions that are not considered in Eq. (1). Eq. (1) can also be used to predict the deformation length.

The optimum conditions were inserted into Eq. (1) again to calculate the deformation length and its variation. The corresponding axial forces are shown in Table 7. The resultant deformation length was 1.399 mm, the variation is 0.0014 mm, and the 95% confidence interval was 1.399 ± 0.0752 mm.

Table 8 Noise simulation using tolerance as noise

	LW thickness (mm)	GW thickness (mm)	BW thickness (mm)	GW height (mm)	GW angle (°)	Axial force (kN)
1	0.9894	0.3880	0.6300	1.746	53.35	195
2	0.9894	0.4000	0.6300	1.800	55.00	200
3	0.9894	0.4120	0.6300	1.854	56.65	200
4	1.0200	0.3880	0.6300	1.800	56.65	200
5	1.0200	0.4000	0.6300	1.854	53.35	205
6	1.0200	0.4120	0.6300	1.746	55.00	197
7	1.0506	0.3880	0.6300	1.854	55.00	202
8	1.0506	0.4000	0.6300	1.746	56.65	196
9	1.0506	0.4120	0.6300	1.800	53.35	203

4.4 Confirmation of the design under optimum conditions

For the simulation in section 4.2, exact values of each parameter were used. In reality, however, it is impossible to manufacture products with exact dimensions. Since the product always has tolerances, it is necessary to consider them when simulating the design. Two kinds of simulation methods were used to confirm the optimum conditions with tolerances. The first method is a noise simulation method that interprets the tolerance as an error parameter, as in section 3.1.2. The second method is a Monte Carlo analysis. When generating parameters in a Monte Carlo simulation, each variable is generated by a normal distribution, of which the mean is the value of each optimal condition, and the standard deviation is set to 0.0245, which is applied in section 3.1.2.

The results of the noise simulation under optimum conditions are given in Table 8. The average axial force was 200.05 kN, and the S/N ratio was 35.79. These results are exactly the same as the results obtained in section 4.2 under optimum conditions. This occurred because the algorithm was identical, even though we used orthogonal array tables of different sizes. As a second method to confirm the optimum conditions with tolerance, the Monte Carlo method was used. To increase the accuracy, we performed the Monte Carlo method three times and each simulation used 30 randomly generated data sets. The average axial force and the S/N ratio are shown in Table 9. The axial forces were 200.14, 200.52, and 200.37 N, and the S/N ratios were 37.32, 35.61, and 36.33. The axial force obtained from the noise simulation and the Monte Carlo are very similar to the axial force obtained under noise-free optimization conditions. Both the noise simulation and Monte Carlo results are also within the 95% confidence interval of the additive model. This proves that the obtained optimum conditions are sufficiently reliable.

Table 9 Monte Carlo simulation results

	1st Simulation		2nd Simulation		3rd Simulation	
	Mean	Sd.	Mean	Sd.	Mean	Sd.
LW thickness (mm)	1.02	0.023	1.02	0.029	1.02	0.024
GW thickness (mm)	0.40	0.029	0.40	0.021	0.40	0.024
BW thickness (mm)	0.63	0.020	0.63	0.020	0.63	0.025
GW height (mm)	1.80	0.023	1.81	0.023	1.80	0.029
GW angle (°)	55.00	0.021	55.0	0.020	55.01	0.022
Axial force (kN)	200.14		200.52		200.37	
S/N ratio	37.32		35.61		36.33	

5. Conclusions

In this study, an inexpensive smart washer was proposed to confirm the axial force of bolts. This washer was designed to measure the axial force exactly, to be robust against tolerances, and to be highly deformable. An L81 orthogonal array table was chosen to investigate the main effects and interactions of the parameters. Noise simulations including interactions were performed, and the interactions were negligibly small. The optimum conditions were determined for maximum robustness and deformation. The measured axial force was 200 kN. The noise simulation and Monte Carlo method showed very similar results when comparing the washer performance under optimum conditions. An additive model was derived and compared with the noise simulation results, which showed that the results obtained with the optimum conditions satisfied the 95% reliability condition of the additive model.

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