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Robust Design of an Automobile Ball Joint Considering the Worst-Case Analysis

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차량용 볼조인트의 최악 조건을 고려한 강건 설계

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ABSTRACT

An automobile ball joint is the element for connecting the control arm and the knuckle arm, allowing rotational motion. The ball joint consists of the stud, plug, socket, and seat. These components are assembled through the caulking process that consists of plugging and spinning. In the existing research, the pull-out strength and gap stiffness were calculated, but we did not consider the uncertainties due to the numerical analysis and production. In this study, the uncertainties of material property and tolerance are considered to predict the distributions of pull-out strength and gap stiffness. Also, pull-out strength and gap stiffness are predicted as the a distribution rather than one deterministic value. Furthermore, a robust design applying the Taguchi method is suggested.

Keywords : Ball Joint(볼 조인트), Robust Desing(강건설계), Uncertainty(불확실성),Worst-Case Analysis(최악-조건 해석), Taguchi Method(다구치 방법)

1. Introduction

An automobile ball joint is the element that can be rotated in every degree of freedom for the steering, connecting suspension and steering systems. In existing research1,2, the quality of caulking process and the structural performance were predicted by performing numerical analysis.

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The caulking process of the ball joint is the work of assembling stud, plug, socket and seat. Through this process, the ball joint is assembled as the plastic deformation generates at the top of the socket.

Structural responses of pull-out strength, gap stiffness, operating torque, etc. are commonly considered in developing a ball joint. A car maker or part manufacturer has its own design requirements related to the structural responses. It is known that among the structural responses, pull-out strength and gap stiffness are the most important performance in the design process. The pull-out strength is the required force to pull the stud out from the ball joint assembly when applying the vertical load on the stud after fixing the bottom1,2. If the pull-out strength is less than the allowable value, the ball joint is considered as an infeasible design. The gap stiffness is evaluated base on the value of displacement that generates when applying load on the stud after fixing the socket. If the gap stiffness is too high or too low, it degrades the performance of NVH.

Jang and Sin1,2 calculated the pull-out strength and the gap stiffness using the commercial software called the DAFUL3,4. One of the research objectives was to inspect the caulking quality using three-dimensional dynamic analysis. In addition, in Ref. [1], two shape design variables were defined and the optimum design was suggested by applying the metamodel based optimization technique. In Ref. [2], by applying the design of experiments, the optimum design considering the pull-out strength and gap stiffness was suggested.

The deterministic numerical analysis in the existing research outputs a constant pull-out strength and gap stiffness since it does not include any noise factor. However, the pull-out strength and the gap stiffness have the distributions due to the variation on the noise factor, respectively. Thus, it is more realistic to suggest its distribution rather than the deterministic value in predicting the pull-out strength and the gap stiffness. In this research, the noise factors are selected as the material properties of the seat and the tolerances of design variables. The material of the seat, one of the components of ball joint, is nylon. The material property of nylon fluctuates relatively heavily when the material test is conducted repeatedly. Thus, nylon's Young's modulus and yield strength are considered as the noise factors. In addition, the dimensions of the stud and the plug have a huge influence on the pull-out strength and the gap stiffness. Thus, they are defined as the design variables, while their tolerances are set up as the noise factors. Then, the parameter design scheme proposed by the Taguchi method is applied for the robust design. The final design is recommended by considering the worst case of the structural responses.

The three-dimensional flexible multibody analysis in Refs. [1] and [2] was performed using a commercial software, DAFUL3,4. The pull-out strength and gap stiffness analysis was sequentially performed, following the caulking process. This sequential analysis has a strong advantage in that it can be analyzed by considering the residual stress. However, one analysis time for the initial design took 71 hours for a caulking analysis, 10 hours for a pull-out strength calculation by using the 3GHz PC2. Furthermore, the pull-out strength calculations could be carried out dozens or hundreds times to obtain a robust design. Thus, when using the three-dimensional analysis, it is impossible to compute the robust design solution due to the long calculation time. In this research, the two-dimensional analysis substitutes for the three-dimensional analysis using a commercial software, Abaqus5.

2. Pull-Out Strength Analysis of the Ball Joint

2.1 Three-dimensional analysis of the ball joint using DAFUL

The ball joint used in this study is the product being installed in the midsize car of A company. This ball joint consists of stud, plug, socket and seat, and the three-dimensional analysis using the flexible multibody dynamics was already conducted in the existing research 2. This research is the follow-up study of Ref. [2]. The base design of the ball joint was completed by using the CATIA. Based on this, the three-dimensional dynamic analysis was performed, and the finite element model of each component was shown as in Fig. 1. When analyzing the caulking process, the roller and the pusher were modeled as the rigid body1,2 .

The analysis of the caulking process can be summarized as follows. First, a temporarily assembled ball joint is set in the caulking machine. Then, the bottom of the socket is fixed to a jig, and the pusher goes down to fix the temporarily assembled ball joint. After that, the pusher stops, and two rolling rollers drop to the top of the socket. At this time, the plastic deformation generates at the top of the socket, leading to bending the top of the socket and attaching it to the plug. The contacts that should be considered in the analysis are represented in Fig. 2.

The caulking process can be evaluated qualitatively through the three-dimensional analysis, and inspecting a plastically deformed shape of the socket. The pull-out strength was sequentially performed, following the caulking analysis in the existing research1,2 . However, the three-dimensional analysis induces the excessive computer calculation time. For the boundary condition in the finite element analysis, all the degree of freedoms that define the outer diameter of the socket are fixed. The pull-out strength is determined by investigating the force-displacement curve. In the base design of ball joint, the pull-out strength was calculated as 33kN and shown in Fig. 3. The caulking analysis using the commercial software DAFUL took 71 hours, and the pull-out strength analysis took 10 hours. The flow stress-strain curve, the material and material property of each component, is included in the Ref. [2].

Stress-strain curve, the material and material property of each component, is included in the Ref. [2].

The contact boundary condition is given to the combination with the contacting part. The contact boundary conditions applied to the combination of parts are plug and seat, plug and stud, socket and seat, seat and stud, pusher and plug, roller and socket.

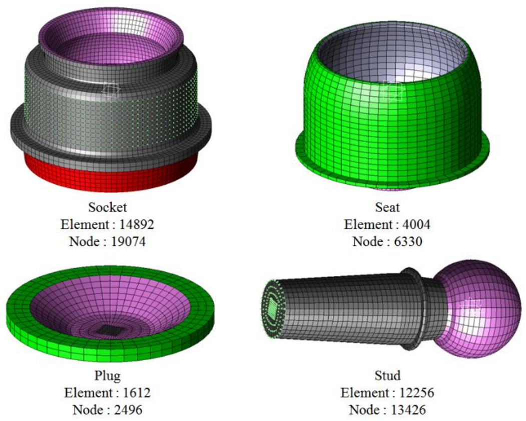

Fig. 1 Finite element model of the ball joint for 3-dimensional analysis

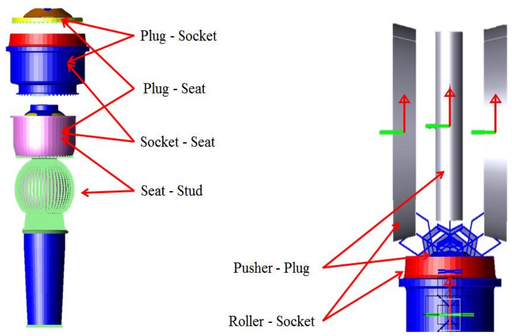

Fig. 2 Contact condition of the ball joint for 3-dimensional analysis

2.2 Two-dimensional analysis of the ball joint using Abaqus

The caulking analysis using three-dimensional flexible multibody dynamics is essential for evaluating the quality of the caulking. On the other hand, it is more efficient to adopt the two-dimensional analysis rather than the three-dimensional analysis for the pull-out strength prediction. Especially, a number of analyses is required to consider the effects of noises in the robust design. If the pull-out strength is obtained from the three-dimensional analysis, it will be impossible to implement the robust design due to excessive computing time. Thus, in this research, the two-dimensional analysis is adopted to perform the pull-out strength analysis of the ball joint.

The CAD model for the two-dimensional analysis is shown in Fig. 4. Because its geometry has the bilateral symmetry, the symmetric condition is imposed on the center line along the y-axis. The boundary condition, loading condition and contact condition are set up in the same way as the three-dimensional analysis. For the pull-out strength analysis using the two-dimensional finite element, the commercial software, Abaqus5 respectively.

In addition, the gap stiffness analysis is performed using the two-dimensional finite element model. The boundary condition for the gap stiffness is the same as that for the pull-out strength analysis. The loading condition was set up as the axial load with the magnitude of F0 applied on the stud. The gap stiffness of the base design was calculated as 0.3 mm.

The difference between the two results is about 10%. In general, a number of analysis are required to include the influence of noise effect in the robust design. When the pull-out strength analysis is performed by three-dimensional analysis, it is sometimes impossible finish the analysis due to excessive computation time. For this reason, we decided that it would be possible to replace the three-dimensional analysis result by the two-dimensional analysis result.

3. Robust Design of the Ball Joint Considering the Noise Factors

The uncertainty of the manufacturing tolerance or the material property may affect the performance of the ball joint. However, the existing research1,2 neglected these uncertainties, and the performance of

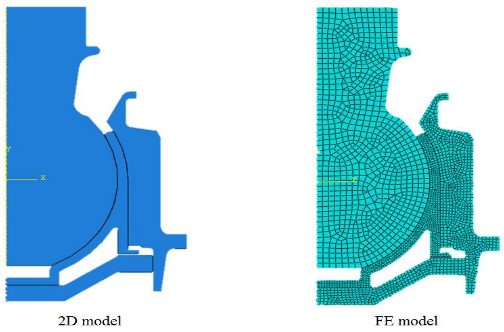

Fig. 3 CAD model and FE model of the ball joint for 2-dimensional analysis

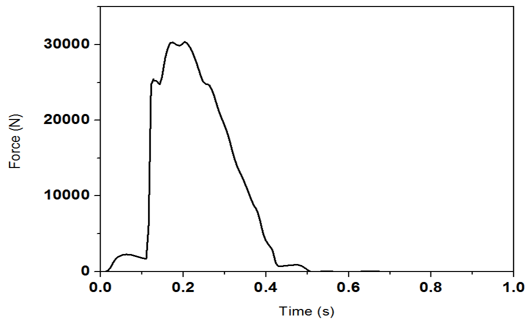

Fig. 4 Force vs. time curve for the pull-out strength (Abaqus)

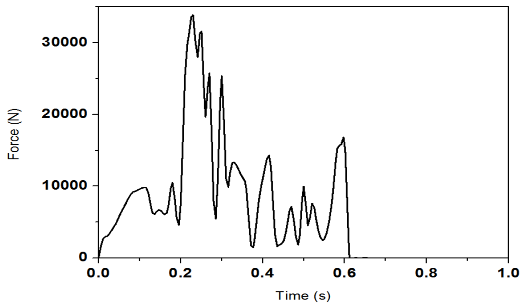

Fig. 5 Force vs. time curve for the pull-out strength (DAFUL)

ball joint was predicted as the deterministic value. In this research, these uncertainties are considered to determine the robust design. The robust design of the ball joint considering the structural responses is suggested by applying the parameter design suggested by Dr. Genichi Taguchi.

3.1 Parameter design in the Taguchi method

The parameter design is applicable for both the product design and the process design. The main purpose of the parameter design is to minimize the distribution of performance that is generated by the uncontrollable design and, at the same time, to find the combination of design variables that makes the mean value of characteristics approach the target value6~9,10-11.

Dr. Taguchi suggested the use of orthogonal array in an efficient way in order to reduce the number of experiments, and defined the SN ratio (signal-to-noise ratio) as the index to evaluate the robustness. The SN ratio is derived from the loss function according to the kinds of characteristic. The SN ratio is expressed as the following equations; they correspond to the characteristics of the smaller-the-better type, larger-the-better type, and nominal-the-best type, respectively6~9,10-11.

$$SN_i = -10\log\left[\frac{1}{n_s}\sum_{j=1}^{n_s} y_{ij}^2\right]$$

for smaller-the-better type characteristic (1)

$$SN_i = -10\log\left[\frac{1}{n_s}\sum_{j=1}^{n_s} \frac{1}{y_{ij}^2}\right]$$

for larger-the-better type characteristic (2)

$$SN_i = 10\log\left[\frac{\overline{y_i^2}}{s_i^2}\right]$$

for nominal-the-best type characteristic (3)

where n_s is the number of experiment considering the noise in i-th experiment, y_{ij} is the characteristic measured in j-th experiment of i-th experiment, $\bar{y}_i$ is the sample mean of the characteristic of i-th experiment, and s_i^2 is the sample variance of the characteristic of i-th experiment.

The robust design is determined as the combination that makes the SN ratio, which is defined in Eqs. (1)~(3), be maximized. Because the SN ratio is derived from the expectation of the loss function, the effect of the average and the standard deviation is related and coupled in many design problems[10-12]. Thus, this research adopts the worst-case analysis considering the average and standard deviation of response.

3.2 Definition of design variables and noise factors

The design variables that are expected to be the largest influence on the pull-out strength are defined in Fig. 6. The shape design variable A is the radius of the ball stud, and the shape design variable B is defined as the angle between x-axis and the socket's slope. The manufacturing tolerances of design variables A and B are set to △A=1.0mm and △B=1.0°, respectively. They are included in the noise factors. The material of the seat is nylon. However, the nylon tends to have a large variation in its material properties when conducting the material experiment. Thus, the nylon's yield strength and Young's modulus are added in the noise factors. The deviations of Young's modulus E and yield strength σy are assumed as △E=1446 MPa and △σy=20 MPa, respectively.

The design variable, called the control factor in DOE (design of experiments), is set to three-level in the design range. It is assumed that the design variable and noise factor have normal distribution as shown in Fig. 7. In Fig. 7, $\bar{x}$, s and △x represent the mean of the design variable, the standard deviation and the tolerance. According to the normal distribution, the probability of the design variable and the noise factor being between the LSL (lower specification limit) and the USL (upper specification limit) is 99.7%. The distance between the LSL and the USL is 6s, thus △x=6s. The levels of the design variable and the noise factor are

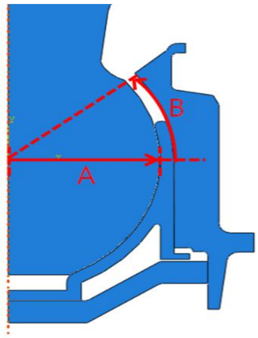

Fig. 6 Design vaiables of the ball joint

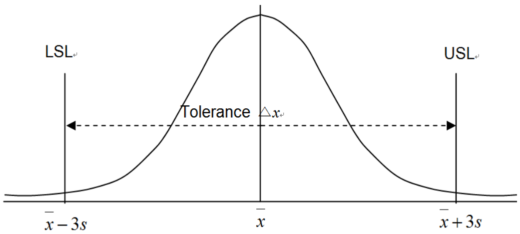

Fig. 7 Normal distribution of design variable

Table 1 Levels of design variables

level	Design Variable		Noise Factor			
	A(mm)	B(deg)	A(mm)	B(mm)	E(MPa)	σ_y(MPa)
1	25.0	30.0	$A-\sqrt{\frac{3}{2}}s_A$	$B-\sqrt{\frac{3}{2}}s_B$	$E-\sqrt{\frac{3}{2}}s_E$	$\sigma_y-\sqrt{\frac{3}{2}}s_{\sigma_y}$
2	26.0	35.0	A	B	E	σ_y
3	27.0	40.0	$A+\sqrt{\frac{3}{2}}s_A$	$B+\sqrt{\frac{3}{2}}s_B$	$E+\sqrt{\frac{3}{2}}s_E$	$\sigma+\sqrt{\frac{3}{2}}s_{\sigma_y}$

Inner Array

No.	Design Variable (level)	
	A	B
1	1	1
2	1	2
3	1	3
4	2	1
5	2	2
6	2	3
7	3	1
8	3	2
9	3	3

1st Outer Array

No.	Noise Factor (level)			
	A	B	E	σ_y
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

⋮

9th Outer Array

No.	Noise Factor (level)			
	A	B	E	σ_y
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Fig. 8 Inner Array and Outer Arrays

represented in Table 1. The initial design is assigned to the second level, the one step lower value than the initial design to the first level while the one step larger value to the third value. The three levels of each noise factor are determined so their mean and variance become A, B, E or σ_y and s_A^2,s_B^2,s_E^2 and $s_{\sigma y}^2$, respectively[6,8,12].

3.3 Conducting of the experiments

Because the number of design variables and the number of levels are two and three, respectively, the number of experiments for the inner array is set to 32=9, considering the full combination. On the other hand, the number of the noise factors is four, and the number of levels is three. Thus, if the full combination experiment is chosen as the outer array, the number of experiments in the outer array becomes 34=81 for one row of the inner array, which requires 9×81=729 experiments for nine rows of inner array. That demands total 729 times finite element analyses. To prevent excessive computing time, the L9(34)orthogonal array is adopted as the outer array. When using the orthogonal array as the outer array, the number of the finite element analysis decreases from 729 to 81. The relation between the inner array and the outer array is shown in Fig. 6.

Through 81 times finite element analyses, the means, the variances and the SN ratios of pull-out strength and gap stiffness are calculated for every row of the inner array. The pull-out strength is classified as the larger-the-better type response. Thus, the SN ratio for the pull-out strength is calculated using Eq. (2). On the other hand, though the gap stiffness could be classified as the nominal-the-best type response, in the given design range, it could be considered as the smaller-the-better type response. Therefore, the SN ratio for gap stiffness is calculated using Eq. (1). The SN ratios, means, variances and worst-case values of pull-out strength and gap stiffness in the inner array are summarized in Table 11. The worst-case responses of pull-out strength and gap stiffness in this research are represented as

$$\overline{p} - 3s_p \tag{4}$$

$$\overline{G} + 3s_G \tag{5}$$

where $\overline{p}$, $\overline{G}$,s_p and s_G are the means and the standard deviations of the pull-out strength and the gap stiffness, respectively.

The pull-out strength and the gap stiffness have their distributions due to the distributions of the noise factors. It is assumed that the distributions of the pull-out strength and the gap stiffness are the normal distribution. When the worst-case response of the structural performance of the ball joint does not violate the border defined as the allowable value for the structural performance, it means that 99.7% of the ball joint products meets the design requirement. From Table 11, it can be seen that the worst-case responses of the pull-out strength have larger than its allowable value fo in No. 7, 8, and 9. Only the worst-case responses of No. 1, 2 and 3 do not satisfy the design requirement related to the gap stiffness. Thus, we can select an optimum design as No. 9 since its worst case of the pull-out strength has the largest value and its worst case of the gap stiffness has lower than the allowable value δ_0.

If we utilize the SN ratio as the index to obtain the robust design, when considering the pull-out strength only, No. 9 is the best, while No. 4 is the best when considering the gap stiffness only. The trade-off decision between the two responses will be made to determine the final robust optimum levels. But, if we do trade-off only using the SN ratio, we will get the solution worse than that from using the worst-case analysis. In this research, No. 9 in the inner array is selected as the final robust solution. That means 99.7% of the ball joint products meets the design requirement. On the other hand, No. 5 in the inner array is the initial design, and just 44.8% of that meets the design requirement for the pull-out strength.

The table below came out via an inner array of Fig.6 with outer arrays. For example, in the first outer array, both of the design variables A and B are one level, and experiments are performed in consideration of 1 level noise factor. 1 level of the design variable is described in Table 1, and the 2 level and 3 level are the same.

Table 2 1th outer array

Exp. No.	Noise Factor				Pull-Out Strength (N)	Gap Stiffness (mm)
	A	B	E	σ_y		
1	24.8	29.8	2604	46	25144	0.253
2	24.8	30.0	2900	50	25557	0.240
3	24.8	30.2	3196	54	24994	0.214
4	25.0	29.8	2900	54	24473	0.225
5	25.0	30.0	3196	46	25559	0.229
6	25.0	30.2	2604	50	25042	0.264
7	25.2	29.8	3196	50	25667	0.233
8	25.2	30.0	2604	54	25423	0.272
9	25.2	30.2	2900	46	24869	0.247

Table 3 2nd outer array

Exp. No.	Noise Factor				Pull-Out Strength (N)	Gap Stiffness (mm)
	A	B	E	σ_y		
1	24.8	34.8	2604	46	22552	0.253
2	24.8	35.0	2900	50	21198	0.253
3	24.8	35.2	3196	54	21465	0.214
4	25.0	34.8	2900	54	22221	0.225
5	25.0	35.0	3196	46	20798	0.229
6	25.0	35.2	2604	50	21051	0.264
7	25.2	34.8	3196	50	22573	0.233
8	25.2	35.0	2604	54	21820	0.272
9	25.2	35.2	2900	46	21726	0.247

Table 4 3rd outer array

Exp. No.	Noise Factor				Pull-Out Strength (N)	Gap Stiffness (mm)
	A	B	E	σ_y		
1	24.8	39.8	2604	46	23346	0.253
2	24.8	40.0	2900	50	22937	0.253
3	24.8	40.2	3196	54	23858	0.214
4	25.0	39.8	2900	54	22328	0.225
5	25.0	40.0	3196	46	22833	0.229
6	25.0	40.2	2604	50	23389	0.264
7	25.2	39.8	3196	50	25071	0.233
8	25.2	40.0	2604	54	24972	0.272
9	25.2	40.2	2900	46	25489	0.247

Table 5 4th outer array

Exp. No.	Noise Factor				Pull-Out Strength (N)	Gap Stiffness (mm)
	A	B	E	σ_y		
1	25.8	29.8	2604	46	25452	0.197
2	25.8	30.0	2900	50	25185	0.175
3	25.8	30.2	3196	54	24871	0.156
4	26.0	29.8	2900	54	25380	0.137
5	26.0	30.0	3196	46	25518	0.139
6	26.0	30.2	2604	50	25166	0.152
7	26.2	29.8	3196	50	26461	0.115
8	26.2	30.0	2604	54	26124	0.133
9	26.2	30.2	2900	46	26590	0.118

Table 6 5th outer array

Exp. No.	Noise Factor				Pull-Out Strength (N)	Gap Stiffness (mm)
	A	B	E	σ_y		
1	25.8	34.8	2604	46	26715	0.197
2	25.8	35.0	2900	50	27079	0.175
3	25.8	35.2	3196	54	27423	0.156
4	26.0	34.8	2900	54	29332	0.139
5	26.0	35.0	3196	46	29182	0.139
6	26.0	35.2	2604	50	29433	0.152
7	26.2	34.8	3196	50	32357	0.115
8	26.2	35.0	2604	54	32816	0.133
9	26.2	35.2	2900	46	32761	0.118

Table 7 6th outer array

Exp. No.	Noise Factor				Pull-Out Strength (N)	Gap Stiffness (mm)
	A	B	E	σ_y		
1	25.8	39.8	2604	46	31497	0.197
2	25.8	40.0	2900	50	31504	0.175
3	25.8	40.2	3196	54	31813	0.156
4	26.0	39.8	2900	54	34142	0.138
5	26.0	40.0	3196	46	35032	0.139
6	26.0	40.2	2604	50	33880	0.152
7	26.2	39.8	3196	50	37504	0.115
8	26.2	40.0	2604	54	37672	0.133
9	26.2	40.2	2900	46	37692	0.118

Table 8 7th outer array

Exp. No.	Noise Factor				Pull-Out Strength (N)	Gap Stiffness (mm)
	A	B	E	σ_y		
1	26.8	29.8	2604	46	37628	0.212
2	26.8	30.0	2900	50	37887	0.208
3	26.8	30.2	3196	54	38176	0.205
4	27.0	29.8	2900	54	42866	0.213
5	27.0	30.0	3196	46	43198	0.212
6	27.0	30.2	2604	50	43611	0.219
7	27.2	29.8	3196	50	47780	0.224
8	27.2	30.0	2604	54	47726	0.229
9	27.2	30.2	2900	46	47721	0.227

Table 9 8th outer array

Exp. No.	Noise Factor				Pull-Out Strength (N)	Gap Stiffness (mm)
	A	B	E	σ_y		
1	26.8	34.8	2604	46	44962	0.212
2	26.8	35.0	2900	50	45106	0.208
3	26.8	35.2	3196	54	45853	0.205
4	27.0	34.8	2900	54	48582	0.213
5	27.0	35.0	3196	46	54897	0.213
6	27.0	35.2	2604	50	49757	0.220
7	27.2	34.8	3196	50	54176	0.224
8	27.2	35.0	2604	54	54056	0.230
9	27.2	35.2	2900	46	55739	0.227

Table 10 9th outer array

Exp. No.	Noise Factor				Pull-Out Strength (N)	Gap Stiffness (mm)
	A	B	E	σ_y		
1	26.8	39.8	2604	46	49503	0.212
2	26.8	40.0	2900	50	49770	0.208
3	26.8	40.2	3196	54	50265	0.205
4	27.0	39.8	2900	54	53840	0.213
5	27.0	40.0	3196	46	54422	0.213
6	27.0	40.2	2604	50	53839	0.220
7	27.2	39.8	3196	50	58958	0.224
8	27.2	40.0	2604	54	59253	0.230
9	27.2	40.2	2900	46	59491	0.227

4. Conclusions

The robust design strategy applicable for the development process of the automobile ball joint is suggested, and the conclusions are as follows

(1) The existing three-dimensional dynamic analysis is substituted with the two-dimensional finite element analysis for predicting the pull-out strength. To investigate the quality of the caulking process,

Table 11 SN ratio and worst case analysis

Exp. No.	SN ratio		Average		Variance		Worst Case	
	Pull-Out Force	Gap Stiffness	Pull-Out Force(N)	Gap Stiffness (mm)	Pull-Out Force(N^2)	Gap Stiffness(mm^2)	Pull-Out Force(kN)	Gap Stiffness(mm)
1	28.0	12.30	25192	0.241	154024	0.00036	24.0	0.298
2	26.72	12.25	21711	0.241	414422	0.00036	19.8	0.298
3	27.51	12.25	23802	0.243	1258341	0.00037	20.4	0.301
4	28.17	16.53	25638	0.146	368958	0.0007	23.8	0.225
5	29.37	16.52	29677	0.147	5946740	0.0007	22.4	0.226
6	30.70	16.53	34526	0.147	6909732	0.0007	26.6	0.226
7	32.54	13.28	42954	0.216	18269440	0.00007	30.1	0.241
8	33.94	13.27	50347	0.217	19789969	0.00007	37.0	0.241
9	34.64	13.27	54371	0.217	16672792	0.00007	42.1	0.241

three-dimensional analysis is required, but for the calculation of the pull-out strength and the gap stiffness, the two-dimensional analysis has sufficient confidence.

(2) In this study, nylon’s Young’s modulus and yield strength are considered as the noise factors. In addition, the tolerance of the diameter of the stud's ball and the tolerance of the angle of the socket’s slope are also considered as the noise factors. It can be seen that the distributions of the pull-out strength and the gap stiffness due to the noise factors should not be neglected. The distributions of the structural responses could be predicted by applying the DOE and the Taguchi method.

(3) We investigated the robust solutions determined from the SN ratio and the worst-case analysis. The final robust solution is selected considering the worst-case analysis, and 99.7% of this ball joint design meets the design requirement. The probability of design success is 55% higher than that of the initial design.

(5) This study focuses on the numerical anlysis. For the future study of this research, it is required to compare the numerical results with the experimental results.

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