MODELLING THE IMPACT BEHAVIOR OF ADVANCED FIBER-REINFORCED SANDWICH STRUCTURES WITH POLYURETHANE FOAM CORE

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Abstract

Within this paper, novel sandwich structures with top layers made of textile-reinforced plastics and polyurethane foam core are investigated with regard to their impact behavior. In contrast to conventional processing technologies, the expansion of the polyurethane foam is used to impregnate the textile reinforcement, creating sandwich top layers and core simultaneously. Given this single-step process, a high adaptability of the resulting mechanical properties can be achieved by varying the geometrical properties, such as foam core density, amount of textile layers and sandwich thickness. A design of experience approach is implemented by using statistical analysis of variance (ANOVA) to investigate the influence of these parameters. The experimental results, such as impact force and absorbed impact energy, gained from a drop weight testing setup, are analyzed and used to create statistical models. As a result, optimized sandwich structures according to stress-related requirements and geometrical constraints can be designed.

1. Introduction

Due to their excellent density related mechanical properties, sandwich structures are established construction methods in many industrial applications. The combination of top layers with high stiffness/strength and a core layer with low density but rather good resistance against shear deformation suggests the use of fiber-reinforced plastics and polymer foams as very promising materials [1-3]. However, the manufacturing technologies for these sandwich structures usually include hand lay-up methods by draping of textiles on prefabricated polymer foams [4-6] or the foam filling into a predefined cavity made of fiber-reinforced face sheets [7, 8].

The layer stackup of sandwich structures with fiber-reinforced top layers can be easily adapted to the demands of the acting loads. Since these structures are already well established, numerous research studies focus on design optimization, improvement of mechanical properties [9, 10] and overcoming the limitations of local failure modes, such as face-core debonding [11] or foam core collapse [12]. By processing sandwich structures using the polyurethane spray coat method, textile reinforcements are directly impregnated with the foam matrix, creating sandwich top layers and core simultaneously. In contrast to conventional sandwich materials, the top layers are impregnated by a cellular matrix and no distinctive bonding zone between top layer and foam core is created.

In the present work, the influence of the geometrical factors sandwich thickness, amount of textile layers and foam core density on the impact performance is evaluated using a statistical design approach. Statistical models are developed based on profound experimental data in the range of 10-50 J impact energy. Among the main motivation for the use of these models is the optimization of the sandwich design for impact loads taking geometrical restrictions, such as limited wall thickness or limitations in total component mass into account.

2. Materials and manufacturing of sandwich structures

Specimens for mechanical characterization were prepared using a polyurethane spray coat method (Figure 1). Prior to the mixing and spraying of the polyurethane matrix inside an open mould, textile preforms are placed into the mould. On top of the liquid reaction mixture, a second textile layer is insertet. Chemical cross-linking results in foam nucleation and expansion, which in turn initiates the impregnation of the textile layers. After final curing, the sandwich sheets are demoulded and prepared for water-jet cutting of specimens.

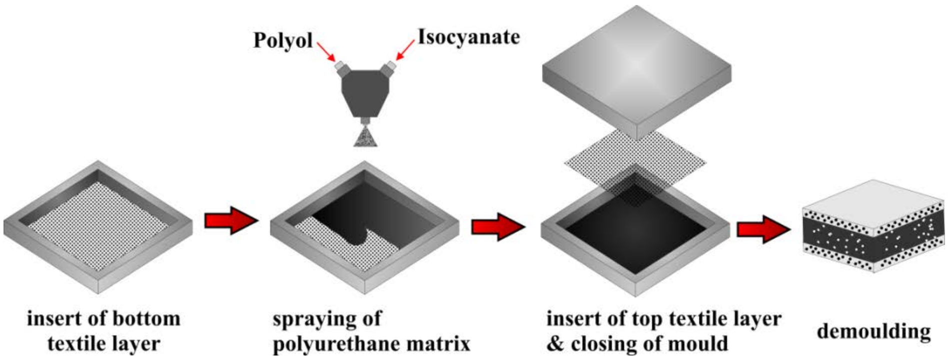

Figure 1. Manufacturing process for producing sandwich structures using the polyurethane spray coat method

Glass-fiber plain weave textiles (Type 92105), provided by *P-D-Interglas Technologies GmbH*, with a grammage of 163 g/m² were processed with a heated flat die at 80 °C. The polyurethane system Elastoflex E 3851/102 (BASF Polyurethanes GmbH) serves as matrix material [13]. The geometrical paramaters, such as mould height and foam density, were adapted according to the statistical design plan between 8 to 12 mm and 650 to 900 kg/m³, respectively.

3. Statistical experimental design and impact-tests

For evaluating the impact behavior, an experimental design using statistical approaches is used. In this paper, a 3^2-factorial design was implemented with three identified factors, each having at least two levels of interest. Since the factor *amount of textile layers* is not continuous, supporting points are inserted, taking three levels for this factor into account. Preliminary processing studies helped to estimate the magnitude of the response change of each factor and to identify predominant processing restrictions [14]. In total, 13 variations of sandwich structures were manufactured according to the following design plan (Figure 2).

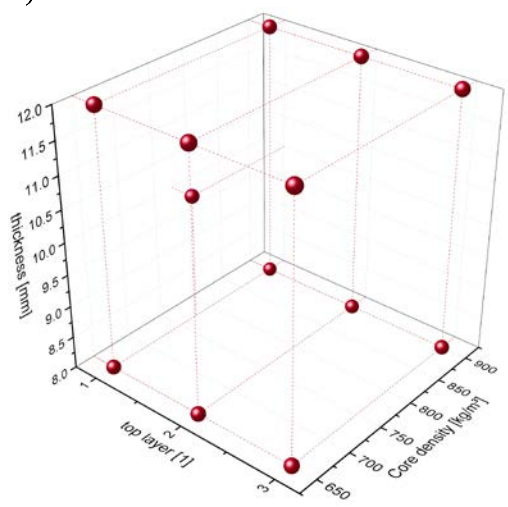

Figure 2. Design model for experimental evaluation of the impact behavior of novel sandwich structures

The impact tests were performed according to the European standard DIN EN ISO 6603-2. Therefore, specimens with a dimension of 60 x 60 mm were produced using water jet cutting. A drop impact tester (Coesfeld GmbH & Co. KG) and a semi-sperical impactor with a defined drop weight of 5.45 kg and a diameter of 16 mm was used at calculated drop heights according to the proposed impact energies between 10-50 J. The applied force and deflection was measured with a moving 25 kN load cell. A light barrier triggers a supporting unit to prevent second impacts due to rebound effects. Analysis and evaluation of the experimental data including calculation of absorbed energy and maximum forces were performed using ORIGINPro 2016G (OriginLab Corporation). For statistical analysis, evaluation and modelling the software JMP Pro 13.1.0 (SAS Institute GmbH) was used.

4. Results and discussion

In general, open and closed type curves for the correlation of impact force and specimen deflection could be distinguished. The areas below the graphs represent the energy absorbed by the specimen. Open curves have a horizontal section at the very end, which occur due to friction between impactor and specimen. In order to determine the true energy absorption, the frictional section is removed. Instead, the last part of the descending curve is extended to the deflection curve using a curve fit. The contact force or impact force is defined as the compressive load and measured constantly between impactor and specimen. In Table 1 the average values of all tested replicates including statistical scatter are presented. However, for statistical modelling the individual results were used instead of the average values.

Table 1. Overview of average absorbed energies including statistical scatter

Layer [1]	**Foam density** [kg/m³]	**Thick -ness** [mm]	**Absorbed Energie** [J]				
			10 J	**20 J**	**30 J**	**40 J**	**50 J**
1	650	8	8,716±369	10,195±0,530	10,348±0,517	11,293±1,031	10,055±1,148
1	650	12	9,436±025	19,007±0,044	25,670±1,487	38,129±0,067	37,335±2,142
1	775	10	9,037±093	16,623±0,431	18,411±1,030	17,918±0,481	18,796±1,037
1	900	8	8,679±432	09,729±0,454	10,326±0,215	12,956±0,365	18,805±1,026
1	900	12	9,120±063	18,066±0,013	27,821±0,752	37,880±0,210	44,071±0,785
2	650	8	8,727±033	18,084±0,996	19,273±0,902	23,268±2,058	25,130±4,536
2	650	12	9,114±029	18,774±0,086	27,989±0,125	36,195±1,524	45,713±1,002
2	900	8	8,676±055	16,845±1,158	15,704±0,537	19,830±1,028	18,498±0,206
2	900	12	9,066±046	18,060±0,124	27,838±0,428	35,784±1,428	43,792±0,233
3	650	8	8,743±023	19,205±0,307	28,100±0,624	34,018±0,939	41,916±0,228
3	650	12	9,058±022	18,896±0,085	29,866±2,011	36,097±0,777	46,599±1,099
3	900	8	8,673±003	18,711±0,145	22,475±0,567	28,436±1,363	34,442±1,397
3	900	12	9,157±119	17,814±0,079	27,664±0,514	36,836±1,072	43,936±0,324

The influence of the factors sandwich thickness (T), foam core density (D) and number of textile layers (L) was studied through analysis of variances for impact energies ranging from 10 – 50 J. Beyond that, interacting effects between the single factors were taken into account. The analysis of variance was performed for a level of confidence of 95 %. In the tables 3-7 (cf. appendix), the factors were evaluated for the selected range of impact energies considering their F-value and p-value. Critical F-value was determined being in the range of $F_c = 2.03 – 1.96$ depending on the degrees of freedom. Factors with “test-F” < F_c and $p > 0.005$ were rejected due to a level of significance below 95 %. From the gained experimental results and their evaluation, factors with statistical significance could be determined (Table 2).

Table 2. Analysis of variance for the tested range of impact energies and siginifcant factors

Factor	10 J Test-F	10 J p-value	20 J Test-F	20 J p-value	30 J Test-F	30 J p-value	40 J Test-F	40 J p-value	50 J Test-F	50 J p-value
D			7.693	0.009	17.280	0.003				
L			76.447	0.001	188.675	0.001	46.106	0.001	76.0398	0.001
T	38.083	0.001	100.59	0.001	715.957	0.001	274.188	0.001	285.396	0.001
D*L					14.628	0.001			13.9220	0.001
D*T					15.832	0.004				
L*T			91.432	0.001	97.905	0.001	42.374	0.001	28.3817	0.001
D*L*T										

From the gained results, it is evident, that the *sandwich thickness* is the dominating factor in terms of impact energy absorption. In the case of rising impact energies, the test-F value increases far beyond the F_{crit} always having a p-value of lower than $p < 0.001$. The factor *foam core density* was found to be statistically significant only at impact energies between 20 J and 30 J. Also, the *amount of layers* has a statistical significance when impact energies are above 10 J. Factor interaction could be determined mainly for the factors L*T above 10 J impact energy and D*L at 30 J and 50 J respectively. Furthermore, a factor interaction of D*T at 30 J was calculated being significant. An interaction of all factors D*L*T was not determined throughout this investigation. By comparing the Test-F value of all results, an increase of this value for all factors with statistical significance until 30 J and a slight decrease from 30 J – 50 J is identified.

By comparing the absorbed impact energy at selected impact energies ranging form 10 J – 50 J in relation to the geometrical parameters sandwich foam core density, sandwich thickness and amount of textile layers, the structures ability of absorbing impact energies can be evaluated. In this context, the relative absorbed energy being the relation of absorbed energy to the impact energy of the impactor is implemented. At low impact energies (10 J), independently from the sandwich structure at least 87 % and up to 94 % of the impact energy was absorbed (Figure 3, left). The tested specimens showed at the impact surface almost no failure of the structure, giving the impression of mainly elastic deformations. The remaining energy, which was not absorbed, is considered being transferred inside the material into heat and friction between impactor and specimen.

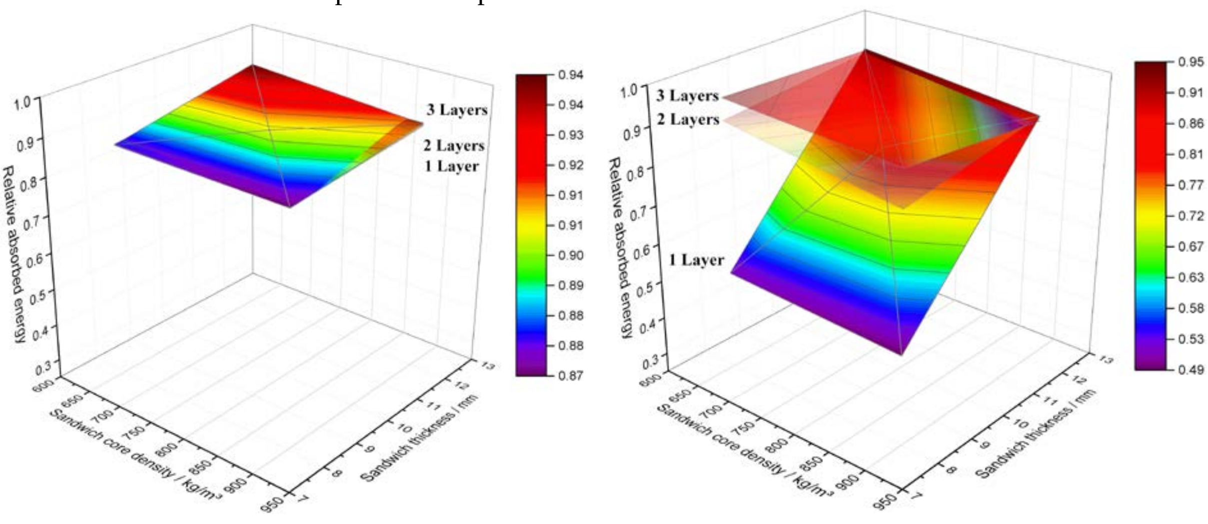

Figure 3. Response curve surface for relative absorbed impact energy at 10 J (left) and 20 J (right) impact energy for various sandwich configurations

With increasing impact energy, the relative absorbed energy for sandwich structures with lower total thickness and lower amount of textile layers is decreasing significantly until 49 % at 20 J (Figure 3, right), to 34 % at 30 J, 26 % at 40 J and 20 % at 50 J (c.f. Figure 4 and Figure 5). The figures also confirm the strong influence of the sandwich thickness at given textile layers and foam core densities on the energy absorbing capability of the sandwich structure. In contrast, the foam core density does only affect the impact behaviour at a low sandwich thickness and sandwich top layers with multiple textile reinforcements, especially at impact energies above 30 J. At the maximum sandwich thickness of 12 mm, the amount of textile layers and the foam core density only have a minor influence on the absorbed impact energy.

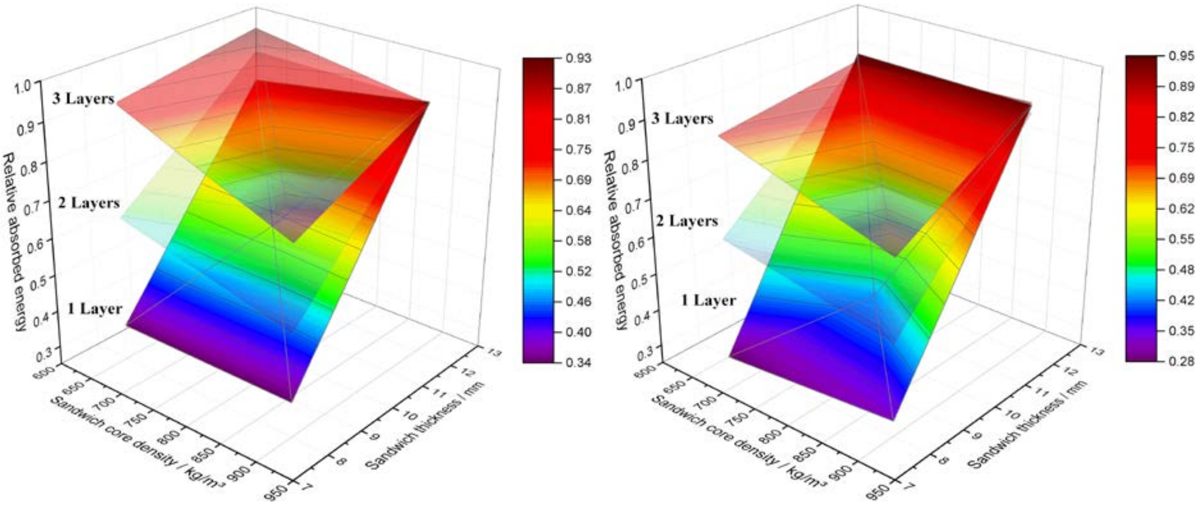

Figure 4. Response curve surface for relative absorbed impact energy at 30 J (left) and 40 J (right) impact energy for various sandwich configurations

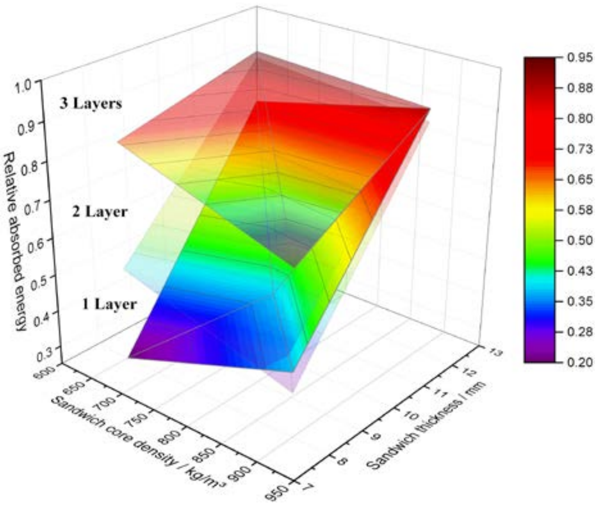

Figure 5. Response curve surface for relative absorbed impact energy at 50 J impact energy for various sandwich configurations

The corresponding statistical models describing the absorbed energy at various impact energies in relation to the significant geometrical factors are given by the following equations (1)-(5). At an impact energy of 10 J, the model for predicting the absorbed energy only relys on the sandwich thickness:

$$\mathbf{E_{10J}(T) = 8939 + 228.2 \cdot \left(\frac{(T-10)}{2}\right).} \tag{1}$$

Comparing experimental and predicted results, the statistical model can be described with $r^2 = 0.51$ and a normalized RMSE = 0.025. With the following equations (2) and (3), the absorbed energies for an impact energy of 20 J and 30 J can be modeled:

$$\mathbf{E_{20J}(D, L, T) = 17107 - 411 \cdot \left(\frac{D-775}{125}\right) + \begin{Bmatrix} -2383; \text{for } L = 1 \\ 833; \text{for } L = 2 \\ 1549; \text{for } L = 3 \end{Bmatrix} + 1487 \cdot \left(\frac{T-10}{2}\right) + \frac{(T-10)}{2} \cdot \begin{Bmatrix} 2800; \text{for } L = 1 \\ -1011; \text{for } L = 2 \\ -1789; \text{for } L = 3 \end{Bmatrix}} \quad (2)$$

$$\mathbf{E_{30J}(D, L, T) = 22747 - 785 \cdot \left(\frac{(D-775)}{125}\right) + \begin{Bmatrix} -4232; \text{for } L = 1 \\ -46; \text{for } L = 2 \\ 4278; \text{for } L = 3 \end{Bmatrix} + 5051 \cdot \left(\frac{(T-10)}{2}\right) + \left(\frac{(T-10)}{2}\right) \cdot \begin{Bmatrix} 3152; \text{for } L = 1 \\ 160; \text{for } L = 2 \\ -3313; \text{for } L = 3 \end{Bmatrix} + \left(\frac{(D-775)}{125}\right) \cdot \begin{Bmatrix} 1316; \text{for } L = 1 \\ -145; \text{for } L = 2 \\ -1172; \text{for } L = 3 \end{Bmatrix} + \left(\frac{(D-775)}{125}\right) \cdot \left(\frac{(T-10)}{2}\right) \cdot 751.} \quad (3)$$

The comparison of experimental results and the model shows the quality of the fit, given by the coefficients of determination for 20 J impact energy ($r^2 = 0.93$ and RMSE = 0.052) and for 30 J ($r^2 = 0.98$ and RMSE = 0.050), respectively. Statistical models for predicting the absorbed energy at impact energies of 40 J and 50 J are developed using the equations (4) and (5):

$$\mathbf{E_{40J}(L, T) = 28750 + \begin{Bmatrix} -5115; \text{for } L = 1 \\ 19; \text{for } L = 2 \\ 5096; \text{for } L = 3 \end{Bmatrix} + 7593 \cdot \left(\frac{(T-10)}{2}\right),} \quad (4)$$

$$\mathbf{E_{50J}(D, L, T) = 33607 + \begin{Bmatrix} -7794; \text{for } L = 1 \\ -323; \text{for } L = 2 \\ 8117; \text{for } L = 3 \end{Bmatrix} + 9383 \cdot \left(\frac{(T-10)}{2}\right) + \left(\frac{(D-775)}{125}\right) \cdot \begin{Bmatrix} 4138; \text{for } L = 1 \\ -1871; \text{for } L = 2 \\ -2267; \text{for } L = 3 \end{Bmatrix} + \left(\frac{(T-10)}{2}\right) \cdot \begin{Bmatrix} 3753; \text{for } L = 1 \\ 2086; \text{for } L = 2 \\ -5839; \text{for } L = 3 \end{Bmatrix}.} \quad (5)$$

The factors $r^2 = 0.76$, RMSE = 0.176 for 40 J and $r^2 = 0.94$, RMSE = 0.099 confirm a rather good agreement between experimental results and the model.

5. Conclusions

In the present work, a statistical experimental design approach was used to evaluate the influence of the geometrical factors sandwich thickness, foam core density and amount of textile layers on the absorbed impact energy. Experimental data in the range of 10 J – 50 J impact energy were evaluated and factors with statistical significance including factor interaction were determined. The dominating factor for all studied impact energies is the sandwich thickness followed by the amount of textile layers. With the gained statistical models, predictions of the absorbed impact energy could be determined in a certain range of reliability. The plots of the response surfaces in relation to the studied factors help to optimize the design of the sandwich structures according to impact loads.

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Appendix

Table 3. Analysis of variance for 10 J impact energy

Factors	SDQ	Mean square	Df	Test-F	p-value
D	44817	44817	1	0.815	0.375
L	85575	42788	2	0.778	0.469
T	1874435	1874435	1	34.09	0.001
D*L	57031	28516	2	0.519	0.601
D*T	2806	2806	1	0.051	0.823
L*T	69628	34814	2	0.519	0.601
D*L*T	76742	38371	2	0.698	0.506
Error	1484547	54983	27	-	-
Total	3695580	-	38	-	-

Table 4. Analysis of variance for 20 J impact energy

Factors	SDQ	Mean square	Df	Test-F	p-value
D	6089708	6089708	1	6.690	0.015
L	121026167	60513083	2	66.473	0.001
T	79624688	79624688	1	87.467	0.001
D*L	117131	58565.5	2	0.064	0.001
D*T	72343	72343	1	0.080	0.780
L*T	144749495	72374748	2	79.503	0.001
D*L*T	561800	280900	2	0.309	0.737
Error	24579058	910335	27	-	-
Total	376820390	-	38	-	-

Table 5. Analysis of variance for 30 J impact energy

Factors	SDQ	Mean square	Df	Test-F	p-value
D	22175309	22175309	1	16.433	0.004
L	484237517	242118759	2	179.421	0.001
T	918758742	918758742	1	680.842	0.001
D*L	37542062	18771031	2	13.910	0.001
D*T	20316354	20316354	1	15.055	0.006
L*T	251275778	125637889	2	93.103	0.001
D*L*T	779530	389765	2	0.289	0.751
Error	36435021	1349445	27	-	-
Total	1771520313		38	-	-

Table 6. Analysis of variance for 40 J impact energy

Factors	SDQ	Mean square	Df	Test-F	p-value
D	13234438	13234438	1	1.985	0.170
L	698080600	349040300	2	52.345	0.001
T	2075693857	2075693857	1	311.288	0.001
D*L	16962321	8481160	2	1.272	0.297
D*T	13825135	13825135	1	2.073	0.161
L*T	641566295	320783148	2	48.107	0.001
D*L*T	25761168	12880584	2	1.932	0.164
Error	180038195	6668081	27	-	-
Total	3665162009	-	38	-	-

Table 7. Analysis of variance for 50 J impact energy

Factors	SDQ	Mean square	Df	Test-F	p-value
D	2565496	2565496	1	0.2274	0.6373
L	1688967338	844483669	2	74.8389	0.001
T	3169556758	3169556758	1	280.889	0.001
D*L	309230379	154615189	2	13.7021	0.001
D*T	14093642	14093642	1	1.249	0.2736
L*T	630403949	315201974	2	27.9335	0.001
D*L*T	22952727	11476363	2	1.017	0.3751
Error	304668489	11284018	27	-	-
Total	6142438778	-	38	-	-