Journal of Current Science and Technology, January-April 2022 Vol. 12 No. 1, 32-42

ISSN 2630-0656 (Online)

Cite this article: Bhat, R., Mohan, N., & Sharma, S. (2022, January). Revised adjusted factor for delamination measurement in drilling of composites. *Journal of Current Science and Technology, 12*(1), 32-42.
DOI:

Journal of Current Science and Technology

Journal homepage: https://jcst.rsu.ac.th

Revised adjusted factor for delamination measurement in drilling of composites

Ritesh Bhat*, Nanjangud Mohan, and Sathyashankara Sharma

Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, India 576104

*Corresponding author; Email: ritesh.bhat@manipal.edu

Received 15 August 2021; Revised 10 September 2021; Accepted 10 September 2021; Published online 25 January 2021

Abstract

Delamination, an inter-ply damage, is a major concern during the drilling of FRP composites. It is evident from past studies that the focus of the researchers has been mostly on reducing the delamination damages by optimising the input parameters, cutting parameters, tool geometry parameters and work materials properties, rather than improving the model for quantifying the delamination factor to get near-to right values. Though Davim’s adjusted model overcomes the demerits of mostly proposed models, it is believed to give the exaggerated values of the delamination factor. Thus, the present study proposes a revised basic two-dimensional model to quantify the delamination factor for fibre-reinforced polymer composites, while addressing the exaggeration effect caused by the most commonly used adjusted delamination factor model. The developed model in this work resulted from combining two prior stated models: Davim’s adjusted model and Da Silva's minimum delamination factor model. The proposed model is validated experimentally and reconfirmed with additional experiments concerning its applicability and efficacy. The delamination damage in this work is characterised by the peel up mechanism for the experimental validation purpose. The results indicate that the exaggeration effect is reduced by 13 to 15% in determining delamination factor value using the proposed model, compared to the existing two-dimensional adjusted factor model.

Keywords: *composites; damage analysing models; delamination; drilling; fibres.*

1. Introduction

Drilling is a frequently practised inevitable machining process in the industry due to the need for fibre reinforced polymer (FRP) component assembly (Davim, Reis, & António, 2004). Delamination, an inter-ply damage, is a major concern during the drilling of FRP composites. It tends to reduce the structural integrity of the laminates, decreasing the assembly tolerance and deteriorating the long-term performance of the component (Ho-Cheng & Dharan, 1990; Liu, Tang, & Cong, 2012). Even though the last two decades have seen several researchers analysing the various conditions for minimising the mentioned damage mechanism, the problem persists (Hejjaji, Singh, Kubher, Kalyanasundaram, & Gururaja, 2016; Kumar & Singh, 2015). For example, Abrão et al. (2008) focused on investigating the relationship between the thrust force and the delamination damages in FRP composites, while varying the drill materials and geometries. Gaitonde et al. (2008) focused on optimising the cutting parameters and drill point angle values to reduce the delamination damage caused while drilling FRP composites. Ficici & Ayparcasi (2015) and Ficici, Ayparcasi, and Unal (2017) attempted to optimise the speed and feed to reduce delamination while drilling FRP composites. Panneerselvam, Raghuraman, and Vidyasundar (2014) tried to reduce the delamination damages in FRP composites by varying the cutting parameters and drill diameters. Palanikumar et al. (2016) and Srinivasan et al. (2017) investigated the effect of the cutting parameters involved in drilling FRP composites to minimise the cutting energy and the delamination effect.

Karimi et al. (2017) attempted to optimise the feed and speed in the drilling of woven FRP composites to minimise the delamination damage induced in them. Sorrentino, Turchetta, and Bellini (2018) proposed a novel controlled feed rate approach to reduce the delamination damage caused during the drilling of FRP composites. Liu, Qi et al. (2018) and Liu, Wu et al. (2018) studied the impact of tool geometry at the tip on the push-down delamination and cutting energy generated during the drilling of FRP composites, and explained the significance of choosing the right tool for minimising drilling-induced damages.

Prakash and Dileep Aditya Dhar (2018) investigated the effect of process parameters on drilling-induced delamination using the vibration signal analysis method. They correlated the effect of process parameters and excess tool wear that causes the damage in the FRP composites. Likewise, several other researchers (Bhat, Mohan, Kulkarni, & Sharma, 2019; Bhat, Mohan, Sharma, Shandilya, & Jayachandran, 2019; Gemi, Morkavuk, Köklü, & Gemi, 2019; Tabatabaeian, Baraheni, Amini, & Ghasemi, 2019) have also tried solving the persisting delamination problem in FRP composite drilling. Apart from optimising the cutting conditions, researchers in recent times have also tried to improve the FRP drilled hole quality by controlling the drill induced forces, either by moving on from conventional machining to non-traditional machining (Karataş, Motorcu, & Gökkaya, 2020) or by implementing tool coating conditions (Ekici, Motorcu, & Uzun, 2021). Though enormous work has been done, drilling-induced delamination in FRP composites remains a hot research area, as is evident from the reviewed literature. The quantification of damage and the model used for quantification are as important as optimising the cutting parameters. Even though a quantitative evaluation by calculating the delamination factor plays a significant role in assessing the effect of the principal cutting parameters and the geometry of the drill (Rubio, Abrao, Faria, Correia, & Davim, 2008), the critically reviewed literature indicates that the focus of the researchers has been mostly on optimising the input parameters, cutting parameters, tool geometry parameters and work materials properties, rather than improving the model for quantifying the delamination factor.

Only a few researchers have focused on this area. Chen (Chen, 1997) proposed, for the first time, the concept of delamination factor F_d, which is defined as the ratio of maximum diameter (D_{max}) of the delaminated zone to the drilled hole diameter (D).

Equation (1) denotes the mathematical representation of Chen's model, popularly known as the one-dimensional model for the delamination factor.

$$F_d = \frac{D_{max}}{D} \quad (1)$$

The delamination factor proposed is simple to use. Still, it fails to consider the two-dimensional area concerning the damage caused surrounding the hole. Hence, Mohan et al. (Mohan, Kulkarni, & Ramachandra, 2007) proposed a model for the delamination factor as the ratio of an effective damaged area (A_d) to the area of the drilled hole known as the nominal area (A_{nom}). The proposed model is most popularly known as the two-dimensional model. Equation (2) denotes the mathematical representation of the model proposed by Mohan et al. (Mohan et al., 2007).

$$F_d = \frac{A_d}{A_{nom}} \quad (2)$$

The two-dimensional model undoubtedly yielded better results than Chen's model, but was found accurate only when a regular delamination pattern existed around the drilled hole. Most of the time, the delamination damages surrounding the holes were seen to be of irregular shape. Thus a modified, or most popularly known as the adjusted model for delamination factor (F_{da}), was proposed by Davim (Davim, Rubio, & Abrao, 2007), wherein the contribution of the crack towards the delamination (Chen's model or one-dimensional model) was combined with the damage area contribution (Mohan et al., (2007) model or two-dimensional model). Equation (3) denotes the adjusted model for the delamination factor, wherein the term F_d is determined using Chen's model given in Eq. (1). The term A_{max} represents the area concerning the maximum diameter.

$$F_{da} = F_d + \frac{A_d}{(A_{max} - A_{nom})}\,(F_d^2 - F_d) \quad (3)$$

Besides the discussed models, Tso et al. (Tsao, Kuo, & Hsu, 2012) and Xu et al. (Xu, Li, Mi, An, & Chen, 2018) also proposed models based on the equivalent delamination factor and three-dimensional delamination factor models respectively. However, these models are applied rarely to quantify delamination damages.

Davim's adjusted model is known to be the most accurate and practically applicable model proposed to date, but has been found in recent times to yield an exaggerated value or a higher than the required value of the delamination factor. The reason is the multiplication factor A_d in the numerator. Also, through his work, Silva (2013) indicated the importance of considering the minimum diameter of damage, as the consideration of damage nearest to the periphery of the drilled hole is determined to hold utmost importance, which all the earlier proposed models have neglected.

2. Research objective

Various researchers to date have emphasised the requirement to consider the minimum crack length contribution towards the delamination factor determination. The present work thus focuses on proposing a revised basic two-dimensional model for quantifying the delamination factor, which is a modification of Davim's adjusted model, by combining it with Da Silva's model based on the theory on minimum crack (delamination at the nearest periphery of the drilled hole). The proposed model addresses the exaggerated effect caused by the adjusted model and accommodates the minimum crack propagation.

3. Methodology

3.1 Proposed model for delamination factor

Consider the one-dimensional model proposed by Da Silva (Silva, 2013), based on the minimum delamination diameter given by Eq. (4).

$$F_{d_{min}}=\frac{D_{min}}{D} \qquad (4)$$

Combining the theoretical principle concerning the nearest crack propagation proposed by Da Silva with the theory proposed by Davim (Davim et al., 2007) regarding the significance of combining the effective contribution of damage caused by crack length and area of damage, the revised basic two-dimensional model (F_{rb}) for determining delamination factor can be mathematically given as depicted in Eq. (5).

$$F_{rb}=\gamma\frac{D_{min}}{D}+\omega\frac{A_{max}}{A_{nom}} \qquad (5)$$

In the developed equation, A_{max} is the area corresponding to the diameter of the maximum delamination zone (D_{max}), and A_{nom} is the area corresponding to the diameter of the drilled hole diameter (D). Therefore, the areas are represented mathematically as Eq. (6) and Eq. (7).

$$A_{max}=\frac{\pi}{4}D_{max}^2 \qquad (6)$$

$$A_{nom}=\frac{\pi}{4}D^2 \qquad (7)$$

Replacing the required parameters from Eq. (1), (4), (6), and (7) in Eq. (5), we get,

$$F_{rb}=\gamma F_{d_{min}}+\omega F_d^2 \qquad (8)$$

γ and ω in the proposed model are weights by parts. In the present work, ω is the average damaged area (A_a) ratio to the difference between the maximum damaged area and nominal area. γ is the complement of ω. The mathematical representation of determining A_a and ω is given by Eq. (9) and (10), respectively.

$$A_a=\frac{A_{max}+A_{min}}{2} \qquad (9)$$

$$\omega=\frac{A_a}{A_{max}-A_{nom}} \qquad (10)$$

Since γ is considered the complement of ω, mathematically, it can be expressed in terms of ω, as shown in Eq. (11).

$$\gamma=(1-\omega) \qquad (11)$$

Combining Eq. (8) and Eq. (11), we have

$$F_{rb}=F_{d_{min}}+\omega\left(F_d^2-F_{d_{min}}\right) \qquad (12)$$

From Eq. (8) (9), (10) and (12), the revised basic two-dimensional delamination factor model can be rewritten as Eq. (13).

$$F_{rb}=F_{d_{min}}+\frac{A_a}{(A_{max}-A_{nom})}\left(F_d^2-F_{d_{min}}\right) \qquad (13)$$

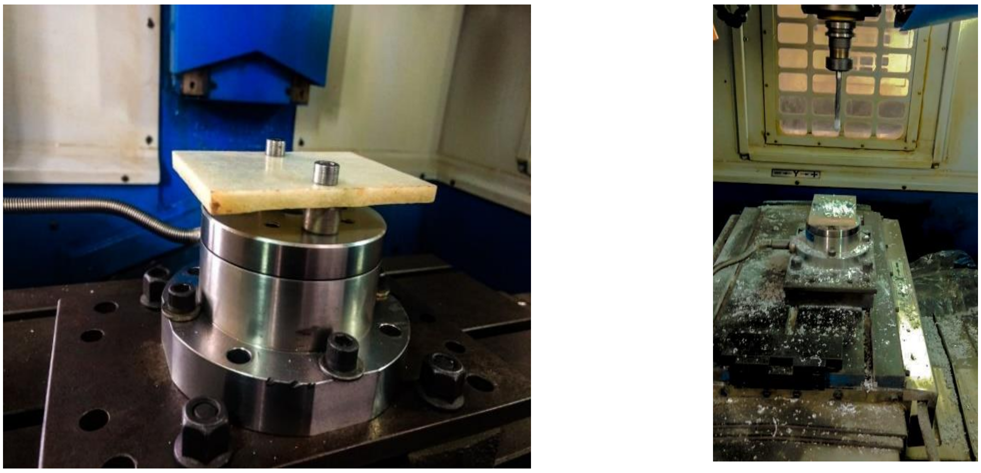
$$\text{If}\begin{cases} A_a \rightarrow (A_{max}-A_0)\text{, then } F_{rb} \rightarrow F_d^2 \\ A_a \rightarrow 0\text{ , then } F_{rb} \rightarrow F_{d_{min}} \end{cases}$$

3.2 Material

E-glass fibre reinforced isophthalic polyester composites material, made using a simple hand lay-up method, is used in the current research work. Three different variants of materials are tested measuring 120 x 80 x 6 mm; 120 x 80 x 8 mm and 120 x 80 x 10 mm. In all the variants, the glass fibre composition is maintained at 33.4 wt.%.

3.3 Experimental validation

The equipment used for drilling all the holes in fibre reinforced composites is the SPARK ACE, a computer numerical control operated vertical machining centre, installed at the machine shop of Manipal Institute of Technology, India. Table 1 provides the technical specifications of the mentioned machine. Figure 1(a) represents a composite specimen placed for drilling, and 1(b) represents the inner view of the VMC with drilled composite.



(a) (b)

Figure 1 Experimental setup with (a) GFRP composite fixed to VMC workbench ready for drilling and (b) Inner view of VMC after drilling composite specimen using an HSS tool

Table 1 Technical specifications of the VMC machine used for drilling

S. No.	Parameter	Specification
1	Table longitudinal axis (x-axis)	300 mm
2	Table cross travel (y-axis)	250 mm
3	Headstock travel (z-axis)	250 mm
4	Table size	500 x 330 mm
5	Maximum Load	1.471 kN
6	Maximum spindle speed	8000 rpm
9	Maximum feed rate	10000 mm/min

A commercially available solid carbide twist drill of 10 mm diameter is used for the hole-making process in the FRP specimens. Speed (rpm), feed (mm/rev) and thickness (t) are considered as the input variables in the experiment, as they are believed to be the most significant factors compared to drill point angle, fibre orientation and fibre volume concerning the delamination damages in drilling the FRP composites (Geng et al., 2019). Table 2 details the input variables with the selected levels used for the accomplishment of the drilling experiment.

Table 2 Parameters and their levels for the drilling experiment

Input parameters	Code	Units	Low (-1)	Med (0)	High (1)
Drilling speed	N	rpm	600	1050	1500
Drilling feed	f	mm/rev	0.1	0.3	0.5
Material thickness	t	mm	6	8	10

A total of 20 combinations of input parameters with three replications, making it a total of 60 experimental runs, is considered for the analysis as per the face-centred central composite design, accommodating central value and blocking. The delaminated zones are studied using a simple imaging technique as the ultrasonic C-Scan test fails for GFRP due to its transparency (Khashaba, 2004). The drilled slabs are photographed using the CANON EOS 1200D, a high-end digital single-lense reflex (DSLR) camera. The images then are imported to the ADOBE® Lightroom. The RAW file format of the images is processed for clarity and saved as a JPEG file format with high contrast and adjusted sharpness at a higher-end for exporting to the AUTODESK® AUTOCAD 2019. The exposure, shadow, blacks and whites are also adjusted to get a clear picture of the delaminated zone. Once imported to AUTODESK® AUTOCAD 2019, the contrast is increased to 100 and brightness is adjusted (36-46) as per the requirement of the image. Then the required diameters are measured. Figure 2 represents a sample of the AUTOCAD measurement procedure for the developed image of a 6 mm thick GFRP drilled slab. Consider hole 56 that is check marked in Figure 2; the outermost circle with a diameter of 14.87 mm represents the maximum diameter of the delaminated zone (D_{max}), which for this case also is the effective diameter (D_d), 10.26 mm represents the drilled hole diameter (D), and 11.24 mm represents the diameter of the minimum delaminated zone (D_{min}). Therefore, the A_{max}, A_{nom} and A_{min} for the discussed hole are 43.394, 20.659 and 24.794 mm^2. For this case, A_{max} is equal to A_d. The F_d, F_{da} and F_{rb} for the said hole thus are calculated using equations (2), (3) and (13) respectively as: 1.449, 2.692 and 2.602.

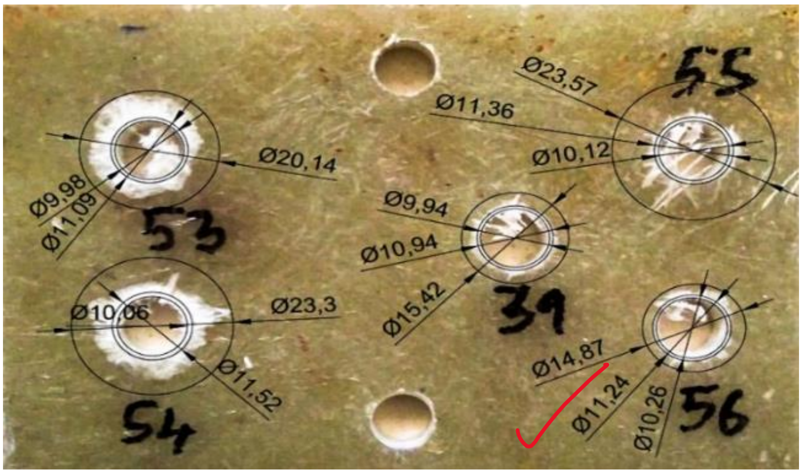


Figure 2 The measured dimensions of the drilled hole using the imaging technique.

Peel up and push down are two different types of delamination mechanisms associated with FRP drilling. The prior occurs around the drilled hole's entry periphery caused by force through the slope of the drill bit flutes, whereas; the latter occurs around the drilled hole's exit periphery resulting from the force of the drill bit on the uncut plies beneath it, which are susceptible to damage due to the decreased thickness (Hassan & Abdullah, 2019). Since the study is all about checking the validity of the proposed delamination quantifying model, only the response variable for the check is quantified through peel up delamination using three different models: Chen's model, Davim's adjusted model, and the proposed model for comparison purposes for each of the 20 holes.

4 Results and discussion

Table 2 provides the average values of peel up delamination using all three models for each of the input parametric combinations. Table 3 provides a sample of few delaminated zones in the composites with the corresponding delamination factor values determined using all three models. On an average, an exaggeration effect reduction of 13.43% is observed between the proposed model and Davim's adjusted model in quantifying the delamination factor, which indicates a significant difference.

Table 3 Calculated values of delamination factors for all the experimental combinations

Ex. No.	N	f	t	F_d	F_{da}	F_{rb}	Fda Vs. Frb
1	1050	0.3	8	1.647	3.235	2.912	9.99%
2	600	0.1	6	1.290	2.193	2.289	4.35%
3	1050	0.1	8	1.658	3.178	2.726	14.25%
4	600	0.1	10	2.009	4.365	3.429	21.46%
5	1050	0.3	8	1.669	3.410	2.891	15.21%
6	1050	0.3	6	1.322	2.227	2.290	2.84%
7	1500	0.5	6	1.285	2.213	2.308	4.28%
8	1050	0.3	8	1.758	3.369	2.836	15.84%
9	1050	0.3	8	1.705	3.538	2.909	17.80%
10	1050	0.3	8	1.928	3.536	3.020	14.60%
11	1500	0.5	10	1.958	4.120	3.598	12.65%
12	1050	0.3	10	1.908	4.296	3.493	18.70%
13	600	0.3	8	1.904	4.053	3.037	25.08%
14	1050	0.3	8	1.849	3.472	2.874	17.24%
15	1500	0.3	8	1.759	3.485	3.023	13.26%
16	1050	0.5	8	1.822	3.567	3.063	14.12%
17	1500	0.1	6	1.258	1.920	2.095	9.11%
18	600	0.5	10	2.290	5.208	3.624	30.41%
19	600	0.5	6	1.460	2.490	2.439	2.06%
20	1500	0.1	10	1.676	3.599	3.405	5.38%
Average Reduction							13.43%

The obtained results show that both the adjusted delamination factor and the proposed revised basic two-dimensional (2-D) delamination models yield a better result than Chen's one-dimensional factor. Comparing Davim's adjusted delamination factor with the proposed model, it is observed that the difference is as low as 2 to 3% for regular patterns. However, for irregular patterns, the reduction percentage is as high as 30.41%. Thus, the obtained result validates the efficacy of the proposed revised basic 2-D delamination model. To further reconfirm the model, a few experiments were conducted again with different values. Table 4 represents the calculated delamination factors for an additional set of experiments.

Table 4 Samples represent the processed images and corresponding delamination factors

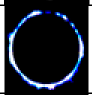
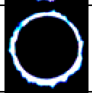
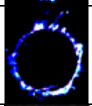
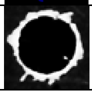
Images after processing	Fd	Fda	Frb	Difference between Fda and Frb
	1.658	3.178	2.726	14.25%
	1.958	4.120	3.598	12.65%
	1.285	2.213	2.308	4.28%
	1.908	4.296	3.493	18.70%
	2.290	5.208	3.624	30.41%

Table 5 Calculated values of delamination factors for all the experimental combinations

Ex. No.	N	f	t	Fd	Fda	Frb	Fda Vs. Frb
1	1500	0.1	6	1.366	2.109	2.158	2.36%
2	825	0.2	6	1.404	2.335	2.293	1.77%
3	1275	0.4	6	1.243	2.099	2.245	6.96%
4	1500	0.5	6	1.287	2.220	2.297	3.47%
5	1500	0.1	6	1.533	2.277	2.138	6.13%
6	1500	0.1	8	2.018	3.641	2.826	22.39%
7	825	0.2	8	1.945	3.850	2.876	25.29%
8	1275	0.4	8	1.730	3.628	2.996	17.41%
9	1500	0.5	8	2.225	3.833	2.980	22.26%
10	1500	0.1	8	1.688	3.164	2.778	12.18%
11	1500	0.1	10	2.073	4.281	3.359	21.54%
12	825	0.2	10	2.062	4.484	3.487	22.23%
13	1275	0.4	10	2.026	4.283	3.486	18.60%
14	1500	0.5	10	2.164	4.822	3.571	25.95%
15	1500	0.1	10	1.858	3.971	3.476	12.47%
Average Reduction							14.73%

In the reconfirmation experiment, the same trend is observed, as seen in the original experiments. An average reduction of 14.73%, approximately 15%, is observed when the proposed revised basic 2-D delamination model is compared with the adjusted delamination factor. Thus, the proposed model again outperforms all the earlier models concerning the delamination model in composite drilling. The trends of all three delamination factors are represented through the line graph shown in Figure 2.

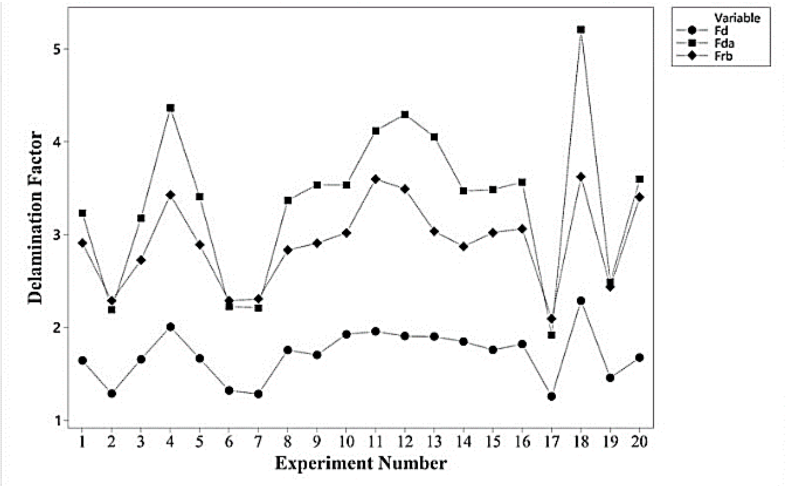


Figure 3 Line diagram representing the comparison between the obtained values of delamination factors

The graph in Figure 3 indicates that the delamination factor value obtained from the proposed model is more efficient than the values determined using the one-dimensional model. Besides, in most cases the proposed model has yielded a lower value than the exaggerated values given by the adjusted models. In the line graph, the values of F_{rb} lies between the values of F_{da} and $F_{d.}$ A better result is obtained because the proposed model considers the contribution of an effective damaged area and major crack zone and the contribution of the minor crack zone.

Besides, the multiplication effect is also reduced due to the replacement of A_d by A_a in the proposed model. The only way to quantify Delamination damage, whether peel up or push down, is through the delamination factor calculated using the models. Though the models are an approximation based on certain assumptions, it is the only way to determine the intensity of the delamination damage in the FRPs. It is thus preferred to have a model, which quantifies the damage in its best possible manner, by accommodating the minor and the major crack length, as both are determined to cause damage to the work material. The proposed model has succeeded in providing a better result by overcoming the demerits of the one-dimensional model, which does not consider the area of the delaminated zone, and also of the two dimensional adjusted models by reducing the exaggeration effect in quantifying. Thus the revision-based model could be used for quantifying the delamination damages in FRP. Moreover, the effect of input variables might also vary with the change in the system of evaluating delamination damage. However, the present work only deals with modelling the quantifying delamination factor and not optimising the input parameters, and thus can be considered for further scope of the presented work. Also, researchers in the field can apply the proposed revision-based model to quantify the delamination caused in different types of FRPs and compare the results with the one calculated with the adjusted model, or the one-dimensional model to further validate its usage as a universal model for composites.

5 Conclusion

Widely used models for determining the delamination factors were investigated, and the best one was identified as Davim's adjusted delamination factor model. The model holds good most of the time but tends to give an exaggerated value of the delamination factor. Thus, a revised basic two-dimensional model was proposed by modifying the existing Davim's model by combining it with Da Silva's minimum delamination model. The model was tested using an experimental analysis wherein an FRP was drilled with a solid carbide tool. Speed, feed and material thickness were varied in the experimental analysis and peel up delamination was quantified using all three delamination models (F_d, F_{da}, F_{rb}). The proposed revision in the adjusted delamination factor proved to yield a better result as the exaggeration effect was reduced by 13 to 15%.

6. References

Abrão, A. M., Rubio, J. C. C., Faria, P. E., & Davim, J. P. (2008). The effect of cutting tool geometry on thrust force and delamination when drilling glass fibre reinforced plastic composite. *Materials and Design*, *29*(2), 508-513. DOI: https://doi.org/10.1016/j.matdes.2007.01.016

Karataş, M. A., Motorcu, A. R., & Gökkaya, H. (2020). Optimization of machining parameters for kerf angle and roundness error in abrasive water jet drilling of CFRP composites with different fiber orientation angles. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *42*(4), 1-27. DOI: https://doi.org/10.1007/s40430-020-2261-2

Bhat, R., Mohan, N., Kulkarni, S. M., & Sharma, S. (2019). Predictive analysis of peel up delamination in glass fibre reinforced polyester composite drilling. *International Journal of Mechanical and Production Engineering Research and Development*, *9*(Special Issue 2), 694-702.

Bhat, R., Mohan, N., Sharma, S., Shandilya, M., & Jayachandran, K. (2019). An integrated approach of CCD-TOPSIS-RSM for optimising the marine grade GFRP drilling process parameters. *Materials Today: Proceedings*, *19*, 307-311. DOI: https://doi.org/10.1016/j.matpr.2019.07.214

Rubio, J. C., Abrao, A. M., Faria, P. E., Correia, A. E., & Davim, J. P. (2008). Effects of high speed in the drilling of glass fibre reinforced plastic: evaluation of the delamination factor. *International Journal of Machine Tools and Manufacture*, *48*(6), 715-720. DOI: https://doi.org/10.1016/j.ijmachtools.2007.10.015

Chen, W. C. (1997). Some experimental investigations in the drilling of carbon fiber-reinforced plastic (CFRP) composite laminates. *International Journal of Machine Tools and Manufacture*, *37*(8), 1097-1108. DOI: https://doi.org/10.1016/S0890-6955(96)00095-8

Davim, J. P., Reis, P., & António, C. C. (2004). Experimental study of drilling glass fibre reinforced plastics (GFRP) manufactured by hand lay-up. *Composites Science and Technology*, *64*(2), 289-297. DOI: https://doi.org/10.1016/S0266-3538(03)00253-7

Davim, J. P., Rubio, J. C., & Abrao, A. M. (2007). A novel approach based on digital image analysis to evaluate the delamination factor after drilling composite laminates. *Composites Science and Technology*, *67*(9), 1939-1945. DOI: https://doi.org/10.1016/j.compscitech.2006.10.009

Ekici, E., Motorcu, A. R., & Uzun, G. (2021). Multi-Objective Optimisation of Process Parameters for Drilling Fiber-Metal Laminate Using a Hybrid GRAPCA Approach. *FME Transactions*, *49*(2), 356-366. DOI: https://doi.org/10.5937/fme2102356E

Ficici, F., & Ayparcasi, Z. (2015). Effects of cutting parameters on delamination during drilling of Polyphthalamide (PPA) matrix composite material with 30% glass fibre reinforcement. *Acta Physica Polonica A*, *127*(4), 1118-1120. DOI: https://doi.org/10.12693/APhysPolA.127.1118

Ficici, F., Ayparcasi, Z., & Unal, H. (2017). Influence of cutting tool and conditions on machinability aspects of polyphthalamide (PPA) matrix composite materials with 30 % glass fibre reinforced. *International Journal of Advanced Manufacturing Technology*, *90*(9-12), 3067-3073. DOI: https://doi.org/10.1007/s00170-016-9626-9

Gaitonde, V. N., Karnik, S. R., Rubio, J. C., Correia, A. E., Abrão, A. M., & Davim, J. P. (2008). Analysis of parametric influence on delamination in high-speed drilling of carbon fibre reinforced plastic composites. *Journal of Materials Processing Technology*, *203*(1-3), 431-438. DOI: https://doi.org/10.1016/j.jmatprotec.2007.10.050

Gemi, L., Morkavuk, S., Köklü, U., & Gemi, D. S. (2019). An experimental study on the effects of various drill types on drilling performance of GFRP composite pipes and damage formation. *Composites Part B: Engineering*, *172*, 186-194. DOI:

https://doi.org/10.1016/j.compositesb.2019.05.023

Geng, D., Liu, Y., Shao, Z., Lu, Z., Cai, J., Li, X., ... & Zhang, D. (2019). Delamination formation, evaluation and suppression during drilling of composite laminates: a review. *Composite Structures*, *216*, 168-186. DOI: https://doi.org/10.1016/j.compstruct.2019.02.099

Hassan, M. H., & Abdullah, J. (2019). Drilling of fibre-reinforced composites: An innovative tool design. In *Hole-Making and Drilling Technology for Composites* (pp. 47-62). Elsevier. DOI: https://doi.org/10.1016/b978-0-08-102397-6.00004-0

Hejjaji, A., Singh, D., Kubher, S., Kalyanasundaram, D., & Gururaja, S. (2016). Machining damage in FRPs: Laser versus conventional drilling. *Composites Part A: Applied Science and Manufacturing*, *82*, 42-52. DOI: https://doi.org/10.1016/j.compositesa.2015.11.036

Ho-Cheng, H., & Dharan, C. K. H. (1990). Delamination during drilling in composite laminates. *Journal of Manufacturing Science and Engineering, Transactions of the ASME*, *112*(3), 236-239. DOI: https://doi.org/10.1115/1.2899580

Kumar, D., & Singh, K. K. (2015). An approach towards damage-free machining of CFRP and GFRP composite material: A review. *Advanced Composite Materials*, *24*(sup1), 49-63. DOI: https://doi.org/10.1080/09243046.2014.928966

Liu, D. F., Tang, Y. J., & Cong, W. L. (2012). A review of mechanical drilling for composite laminates. *Composite Structures*, *94*(4), 1265-1279. DOI: https://doi.org/10.1016/j.compstruct.2011.11.024

Liu, L., Qi, C., Wu, F., Xu, J., & Zhu, X. (2018). Experimental thrust forces and delamination analysis of GFRP laminates using candlestick drills. *Materials and Manufacturing Processes*, *33*(6), 695-708. DOI: https://doi.org/10.1080/10426914.2017.1376072

Liu, L., Wu, F., Qi, C., Liu, T., & Tian, J. (2018). High-frequency vibration analysis in drilling of GFRP laminates using candlestick drills. *Composite Structures*, *184*, 742-758. DOI: https://doi.org/10.1016/j.compstruct.2017.10.042

Mohan, N. S., Kulkarni, S. M., & Ramachandra, A. (2007). Delamination analysis in drilling process of glass fiber reinforced plastic (GFRP) composite materials. *Journal of Materials Processing Technology*, *186*(1-3), 265-271. DOI: https://doi.org/10.1016/j.jmatprotec.2006.12.043

Palanikumar, K., Srinivasan, T., Rajagopal, K., & Latha, B. (2016). Thrust Force Analysis in Drilling Glass Fiber Reinforced/Polypropylene (GFR/PP) Composites. *Materials and Manufacturing Processes*, *31*(5), 581-586. DOI: https://doi.org/10.1080/10426914.2014.961478

Panneerselvam, T., Raghuraman, S., & Vidyasundar, A. (2014). A study to minimise delamination value during drilling chopped strand mat GFRP material. *International Journal of Machining and Machinability of Materials*, *15*(3-4), 136-146. DOI: https://doi.org/10.1504/IJMMM.2014.060545

Prakash, M., & Dileep Aditya Dhar, P. V. S. (2018). Investigation on the effect of drilling parameters on the tool wear and delamination of glass fibre-reinforced polymer composite using vibration signal analysis. *Journal of Composite Materials*, *52*(12), 1641-1648. DOI: https://doi.org/10.1177/0021998317728109

Silva, D. N. R. da. (2013). *Image processing methodology for assessment of drilling-induced damage in CFRP*. DOI: http://hdl.handle.net/10362/9866

Sorrentino, L., Turchetta, S., & Bellini, C. (2018). A new method to reduce delaminations during drilling of FRP laminates by feed rate control. *Composite Structures*, *186*, 154-164. DOI: https://doi.org/10.1016/j.compstruct.2017.12.005

Srinivasan, T., Palanikumar, K., Rajagopal, K., & Latha, B. (2017). Optimisation of delamination factor in drilling GFR–polypropylene composites. *Materials and Manufacturing Processes*, *32*(2), 226-233. DOI: https://doi.org/10.1080/10426914.2016.1151038

Tabatabaeian, A., Baraheni, M., Amini, S., & Ghasemi, A. R. (2019). Environmental, mechanical and materialistic effects on delamination damage of glass fiber composites: Analysis and optimisation. *Journal of Composite Materials*, *53*(26–27), 3671-3680. DOI: https://doi.org/10.1177/0021998319844811

Tsao, C. C., Kuo, K. L., & Hsu, I. C. (2012). Evaluation of a novel approach to a delamination factor after drilling composite laminates using a core-saw drill. *International Journal of Advanced Manufacturing Technology*, *59*(5-8), 617-622. DOI: https://doi.org/10.1007/s00170-011-3532-y

Xu, J., Li, C., Mi, S., An, Q., & Chen, M. (2018). Study of drilling-induced defects for CFRP composites using new criteria. *Composite Structures*, *201*, 1076-1087. DOI: https://doi.org/10.1016/j.compstruct.2018.06.051

Karimi, N. Z., Heidary, H., Fotouhi, M., & Minak, G. (2017). Experimental analysis of GFRP laminates subjected to compression after drilling. *Composite Structures*, *169*, 144-152. DOI: https://doi.org/10.1016/j.compstruct.2017.01.017