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Defining a Reduced Volume Zone for the Simulation of Burst Test on a Composite Pressure Vessels

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Abstract

A Fibre-Break Model (FBM) developed at Mines ParisTech can predict the burst pressure of high pressure composite vessels. This model uses random values of fibre strength at each Gauss point of the considered vessels meshed with finite element (FE). However, previous studies has determined the optimum FEs to be used on real-scale structures (0.1 mm x 0.1 mm x 8 mm). A simple calculation shows that, on a real-scale pressure vessel, this induces a gigantic number of FEs, hence the extensive computation time. To overcome this problem, the integral range method is proposed to find a reduced volume zone of the vessels, on which an equivalent calculation can be made and gives the same results with the one that employs the FBM on the entire structure.

Keywords: Reduced Volume Method, Composite structures, Pressure vessels, Finite Element Method

1 Introduction

Evaluating the reliability of pressure vessels (PV) made from metallic materials has been understood quite well. However, the future developments by using another materials like carbon fibre composite presents unique challenges due to its material properties. The most interesting properties is that its ability to handle higher load while keeping the total weight of the PV low. This load is coming from the internal pressure, for instance, the normal working pressure for compressed natural gas (CNG) and hydrogen cylinders are 30 and 70 MPa, respectively. With such pressures, they pose some dangers in their vicinity as they might explode catastrophically. It is therefore important to have a method that correctly evaluates the long-term behavior of composite pressure vessels (CPV).

BAM discovered that the existing methodology to evaluate the residual strength of CPV has over-estimated the results [1]. Another method then being proposed by performing the slow burst test where they have found out that the reliability of CPV was altered. These results has also been validated with the Fibre-Break Model (FBM) developed at Mines ParisTech [4]. The model was developed based on the understanding from numerous experimental studies of fibre composite structures and these papers [2, 3, 5] can be used to gain general understanding about the FBM. However, to run the FBM model at the real-scale of composite pressure vessels requires an enormous number of degree of freedom to be solved, which is not efficient enough to be used in the industry.

A method based on the integral range approach is then proposed to define certain volume of the real-scale structure to be evaluated with the FBM. This approach has been developed since around 20 years ago and these papers are worth to be cited, [6, 7, 8, 9]. The objective is to obtain the same statistical predicted properties e.g. failure strength of a real-scale structure by using the FBM only on some part of the real-scale structure. By doing so, the computation time can be reduced. After the reduced volume has been found, this approach needs to be validated with usual tensile experiment or burst test experiment of CPV. Afterwards, the evaluation on real scale structures can be done.

2 Methodology

The reduced volume zone to predict the failure strength (Fs) that behaves like a stationary ergodic random function [SERF] as explained by Lantuejoul [7] must be found. At the beginning, it is not possible to predict how the reduced volume zone looks like. All possibilities therefore should be tested by ensuring these two assumptions:

1. The samples (S) are taken from an object (O=1000 FEs) that is large enough to provide an accurate result.
2. The prediction of Fs is assumed to be a realisation of SERF. (n Monte-Carlo runs produces n Fs)

The assemblies will be decomposed in three direction (1D, 2D, and 3D). The 1D-case are decomposed in x_1, x_2 and x_3 direction while for the 2D-case in (x_1, x_2), (x_1, x_3) and (x_2, x_3) directions as shown in Fig. 1. Each decomposition then will have different number of FEs (S), the decomposition on 1D and 2D cases followed the $S = m^2$ rule where the maximum value of $S = 1024$ and $S = 1000 = m^3$ for 3D case. A density of surface force are applied at their two extremities in the x_1 direction (longitudinal) creating a quasi-static tensile load. The applied load is increasing monotonically in function of time.

The study then continues to evaluate the integral range on the assembly that fulfills the assumptions. Multiple N calculations then will be performed and it is distinguished by the fact that the fibre break values required for these N calculations are obtained by N Monte-Carlo process with the same Weibull function. These N calculations therefore shall give the N fibre break values that will be used to compute its average and standard deviation from each decomposition.

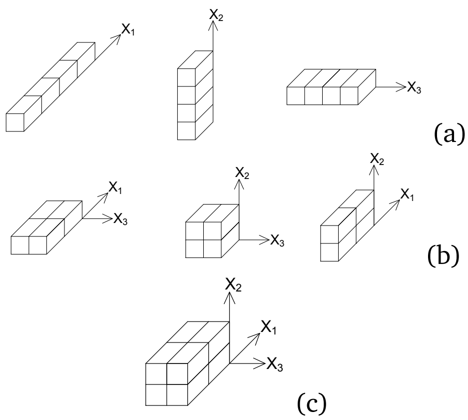
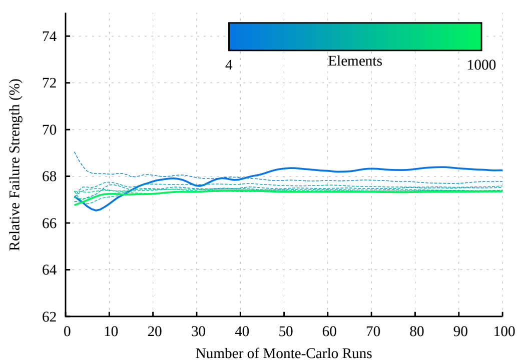


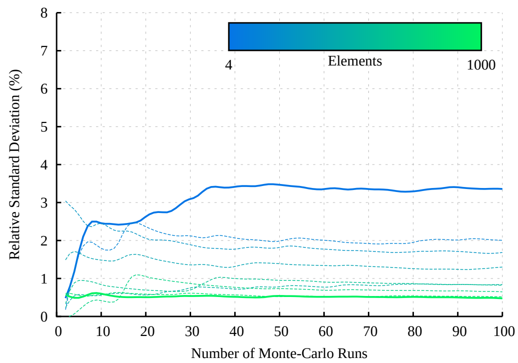
Figure 1: *Assemblies of Finite Elements to find the representative volume of the full-scale structure*

3 Results

3.1 Evaluation of 1^{st} Assumption



(a) *Fs - 3D - Case*



(b) *SD - 3D - Case*

Figure 2: *Relative Averaged Failure Strength (Fs) and Standard Deviation (SD)*

100 Monte Carlo Runs has been performed to ensure that the predicted failure strength gives stable values. From Fig. 2, it can be seen that the results become stable around 50 Monte Carlo Runs, although it also quite sensitive with the number of FEs used in the geometry.

3.2 Evaluation of 2^{nd} Assumption

Integral range method was used to calculate the variance $D_z^2(V)$ of its average value $Z(V)$ over the volume V. For a large V and when the A_3 is finite, equation 1 is valid [6]. D_z^2 is the point variance and A_3 is the integral range of the random function, in this case is the random assignment of the fibre failure strength,

$$D_z^2(V) = D_z^2 \frac{A_3}{V} \quad (1) \qquad D_z^2(V) = D_z^2 \left(\frac{A_3}{V}\right)^\gamma \quad (2)$$

Refer to the study from Dirrenberger et al [6], the term $D_z^2 A_3^\gamma$ in equation 2 can be defined as K. K and γ can then be numerically defined by fitting a power function to the log-log equation below,

$$\log D_z^2(V) = \log K - \gamma \log V \quad (3)$$

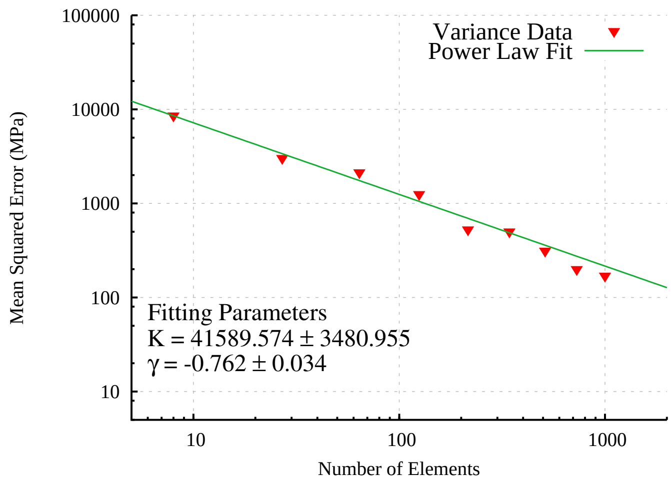


Figure 3: *Log-Graph Fitting*

When the slope of the equation 3 in logarithmic plot is approximately equal to -1, then the assumption is valid. It was found that two assemblies have been found to fulfill the assumption, the $2D - X_2X_3$ Case and $3D$ Case. Fig. 3 shows one of the results with the fitting parameters written on the figure.

4 Integral Range Evaluation

By using the theory of sampling, the reduced volume represented by the number of FEs can be found,

$$\epsilon_{\text{abs}} = \frac{2D_z(V)}{\sqrt{n}} \qquad \epsilon_{\text{rel}} = \frac{\epsilon_{\text{abs}}}{\overline{Z}} \Rightarrow \epsilon_{\text{rel}}^2 = \frac{4D_z^2 A_3^\gamma}{\overline{Z}^2 n V^\gamma} \quad (4)$$

The reduced volume then is defined by rearranging the equation 4,

$$V_{\text{RVE}} = \left(\frac{4K}{\overline{Z}^2 n \epsilon_{\text{rel}}^2}\right)^{\frac{1}{\gamma}} \quad (5)$$

N Monte-Carlo Runs	Intended Relative Error			
	5.00%	1.07%	0.5%	0.11%
	V_{RVE} (Reduced Volume)			
100	1	2	18	**1000**
75	1	3	26	1459
50	1	6	44	2484
25	1	15	108	6168
10	1	49	361	20530
5	2	121	897	50986
2	7	403	2985	169700
1	18	**1000**	7412	421437

Table 1: *Integral Range Analysis*

Such evaluation has also been used in another paper [9]. This study has shown that by using only 18 FEs and performing 1 Monte Carlo run, the failure strength predicted by the FBM is statistically reliable. It is evaluated by having 5% of relative error or in the other way 95% of the confidence value. In this way, the computation time can be reduced as the suggested number of elements is reduced.

5 Conclusions

The proposed method has successfully identified the volume zone that can be used for reducing the computation time. This study therefore has become the groundbreaking approach to use the existing Fibre Break Model from Mines ParisTech for real-scale structure evaluation, i.e composite pressure vessels.

6 Acknowledgements

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