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Physics-based reliability simulation of dental fillings

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Abstract

Developing new dental filling materials is an elaborate process. It is desirable to reduce the time and cost required to develop and test such materials. This work introduces a simulation tool that helps in testing the reliability of the filling before introducing actual models. That means all necessary modifications can be easily accomodated during the simualtion phase. Finite element modeling (FEM) is used to analyze the stress on the dental filling within the tooth. Thermal and structural loads result in normal, shear, and equivalent stresses. The stress results are used to find the fatigue life of the filling. Performing systmatic iterations of this process yields a probability density function (PDF) of the filling life. This PDF is used to calculate the reliability of the filling. A sensitivity analysis is conducted to identify the major factors affecting reliability. After being verified using previous studies on Amalgam-type filling, the presented method can be used to simulate the reliability of any filling design or material. By using this method, We can find how reliable will the filling be after a given life span. On the other hand, for a given reliability level, we can find the expected life of the filling.

Keywords: Amalgam filling, Physics-based reliability simulation, Stress life, Filling reliability, Finite element modeling

1. Introduction

Dental caries is the most common type of tooth disease which occur on the chewing surface of the teeth. Dentists treat the tooth by removing the decayed tooth material with a drill and replacing it with a filler material. In order to improve the servicability of these fillings, new designs and materials with better performance are constantly being sought after. To enhance the testing and verification process of these new fillings, various methods to estimate their life were proposed; [Gonzaga *et al.*, 2011] determined experimentally the slow crack growth and Weibull parameters of five dental ceramics. [Lavelle, 1976] estimated the durability of amalgam restorations using a cross-sectional survey based on 6000 defective restorations spanning a 20-year period. His data showed that amalgam restorations were not as durable as traditionally assumed, with failure on the part of the dental surgeon being the pre-dominant defect. [Qvist *et al.*, 1986] made a survey of the reasons for replacement of amalgam restorations in Denmark. Resaons included failed restorations, bulk fracture of fillings, and loss of fillings. The age of the restorations replaced ranged from 0 to 38 years. In these studies, no quantitative reliability information were provided.

Finite element method has been used successfully to study the stress in teeth as well as in fillings; [Wright and Yettram, 1978] presented a finte element stress analyses of an amalgam restoration. They examined the effects of amalgam setting and thermal expansion on principal stresses and deformation. However, as in other FEM simulations, filling reliability was not addressed. In this work, FEM is used to study the failure of the filling, as well as its expected life and reliability. By doing so, more quantitative information will be available linking the filling life span with its reliability, where the latter decreases as life increases. This means there is no clear-cut life span of the filling, but rather gradual deterioration as age progresses. This work estimates the reliability of dental filling (amalgam) used in the treatment of tooth decay. FEM is used to analyze the stress on the dental filling within thetooth. The stress result is used to find the fatigue life of the filling. Performing systmatic iterations of this process results in a PDF of life. This PDF is used to evaluate the reliability of the filling.

A representative design of the filling is built inside the tooth. The filling model represents the physical and thermal properties of the actual filling.Pressure and thermal loads are imposed on the filling resulting in structural and thermal stresses. The expected service life of the filling is calculated based on the stress level. Accodring to stress-life theory and the S-N curve, damage is expected to start at the end of the filling useful life. The FEM and stress-life models are verified using experimental results available in the literature. The model is subjected to the same conditions and loads that are normally imposed. The stochastic nature of the dimensions, physical properties, and environmental conditions will result in a stochastic response as well. The effects of the different input variables will be compared based on a sensitivity study. Then the major effective parameters will be identified and used in the stochastic simulation. The process will result in the reliability assessment of the dental filling.

2. Filling FEM Model

A commonly used type of filling called Dental amalgam is used in this work. The geometry of the filling is shown in Fig. 1. As there are a good amount of data on this amalgam, it is used to verify the proposed filling reliability simulation method. After being verified, the method can be used to determine the reliability of other filling materials. The tooth model consists of the top Enamel and the lower Dentin parts, while the filling is positioned in the tooth as shown in Fig. 1.Table 1 shows the thermal and mechanical properties of the filling, while the physical properties of the filling are shown in Table 2. The physical and thermal properties of the tooth are shown in Table 3. The model geometry shown in Fig. 1 is meshed as shown in Fig. 2. Pressure and thermal loads are applied on this meshed model, which has 55,000 elements.

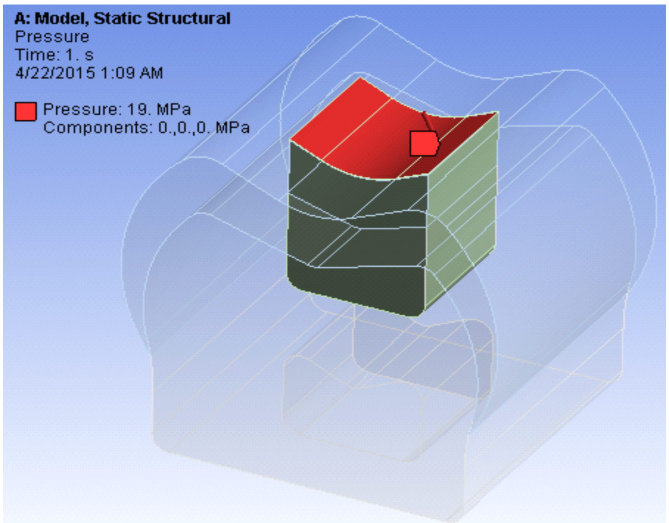

Figure 1: Filing design inside the tooth

Table 1: Filling thermal and mechanical properties

Property	Value	Unit
Density	2100	Kg/m^3
Isotropic Instantaneous Coefficient of Thermal Expansion	8×10^{-6}	$°C^{-1}$
Young's Modulus	1.2×10^{10}	Pa
Poisson's Ratio	0.31	-----
Bulk Modulus	1.0526×10^{10}	Pa
Shear Modulus	4.5802×10^{9}	Pa

Table 2: Filling physical properties

Material	M.E[19,28,29] (Mpa)	Poissons ratio[19, 28,29]	Thermal expansion coefficient(11° c)[26]	Density (G/Cm^3)[26, 27]	Thermal conductivity (cal/cm)[26]	Specific heat (cal g /°c)[26]
Dentin	18,600	0.31	8.3×10^{-6}	2.18	0.0015	0.28
Periodontal ligament	0.69	0.45	-	-	-	3.470
Cortical bone	13,700	0.30	-	1.3	1.4	0.44
Trabecular bone	1,370	0.30	-	1.3	1.4	0.44
Gingiva	3	0.45	-	-	-	3.470
Guttapercha	0.69	0.45	54.9×10^{-6}	-	-	-
Cast Gold	96,600	0.35	14.4×10^{-6}	16.4	0.710	0.03
Porcelain	69,000	0.28	13.0×10^{-6}	2.4	0.0025	0.26
GIC	910	0.3	-	2.16	1.5	0.275
Amalgam	21,200	0.35	22.1×10^{-6}	11.6	0.0055	0.485
Composite	40,000	0.24	27.8×10^{-6}	1.84	0.0026	0.197
Stainless steel	2,10,000	0.28	9.9×10^{-6}	6000	2.1	293

Table 3: Tooth physical and thermal properties

Material	Density (kg / m^3)	Specific Heat J / (kg °C)	Conductivity W / (m °C)	Diffusivity (10^{-6} m^2 / s)	Thermal Expansion (10^{-6} / °C)
Enamel	**3 000**	**750**	**0.92**	**0.41**	**~11**
Dentine	**2 100**	**1260**	**0.63**	**0.24**	**~8**
Zinc phosphate cement	2 590	510	1.17	0.88	35?
Amalgam	11 600	206	23.0	9.6	22-28
Silver	10 500	235	430	175	19.2
Gold	19 300	130	291.7	116	14.4
Water	1000	4185	0.61	0.15	(70)

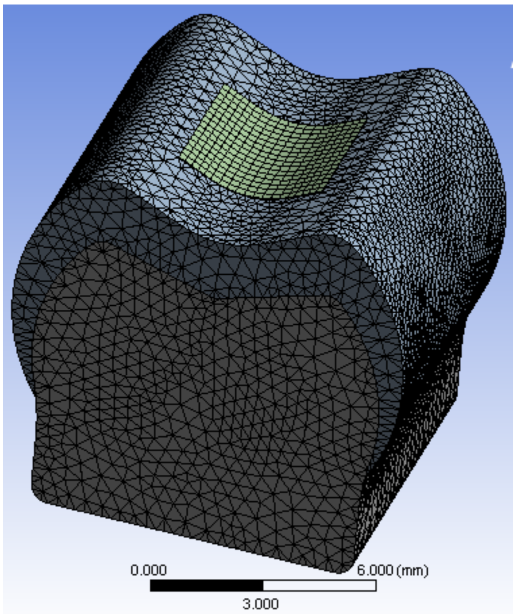

Figure 2: FEM Mesh of the filling and the tooth

3. Simulation of the Filling FEM Model

The purpose of the FEM simulation is to find the maximum stress on the dental filling. The procedure presented by [Al-Habahbeh *et al.* 2009] is used to find the maximum transient stress. Typically, the stress results from exposure to bite pressure and food/drink temperature. The types of applied loading include structural and thermal loads. The structural load is further classified into normal and shear loading. Average temperature experienced by the tooth is 15-55°C, therefore, temperature is increased from 15-55°C in increments of 5°C. Since the average human bite pressure is typically between 19 and 29MPa, [Vallee and Benoit, 2010], pressure values of 19, 24, and 29MPa are examined. Full factorial design (FFD) is used to simulate the loading so as to cover all possible scenarios, [Batra and Jaggi, 2015]. Von Mises stress is calculated to find the resulting loading on the filling. Table 4 lists the stress values resulting from the simulation, as well as the effect of the fatigue correction factor [Al-Habahbeh, 2009]. Fig. 3 shows the thermal and structural stress countours on the filling and the tooth. It is noted that maximum stress occures at the border of the tooth and the filling.

In order to study the relative impact of the various input parameters affecting the reliability. Fig. 4 shows the sensitivity of the maximum shear stress to pressure and filling depth. The pressure is varied from 19-29MPa, while the filling depth is varried from 3-7mm. It is noted that the filling depth has an optimum value of 6mm, and the larget effect on the stress is due to pressure.

Table 4: Stress results for different load scenarios

Pressures (MPa)	Temperature's (°C)	Stress (von Misses)	Corrected stress
19	15	24	48
19	25	21	42
19	35	19.7	39.4
19	45	16.4	32.8
19	55	14.6	29.2
24	15	31	62
24	25	27	54
24	35	25	50
24	45	22.2	44.4
24	55	19.2	38.4
29	15	37	74
29	25	34.1	68.2
29	35	31.4	62.8
29	45	28.6	57.2
29	55	26.6	53.2

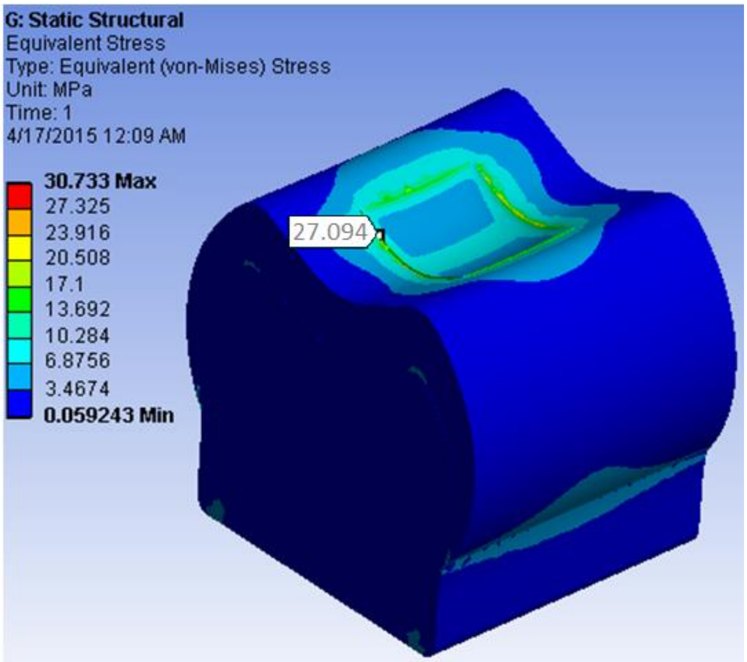

Figure 3: FEM stress distribution.

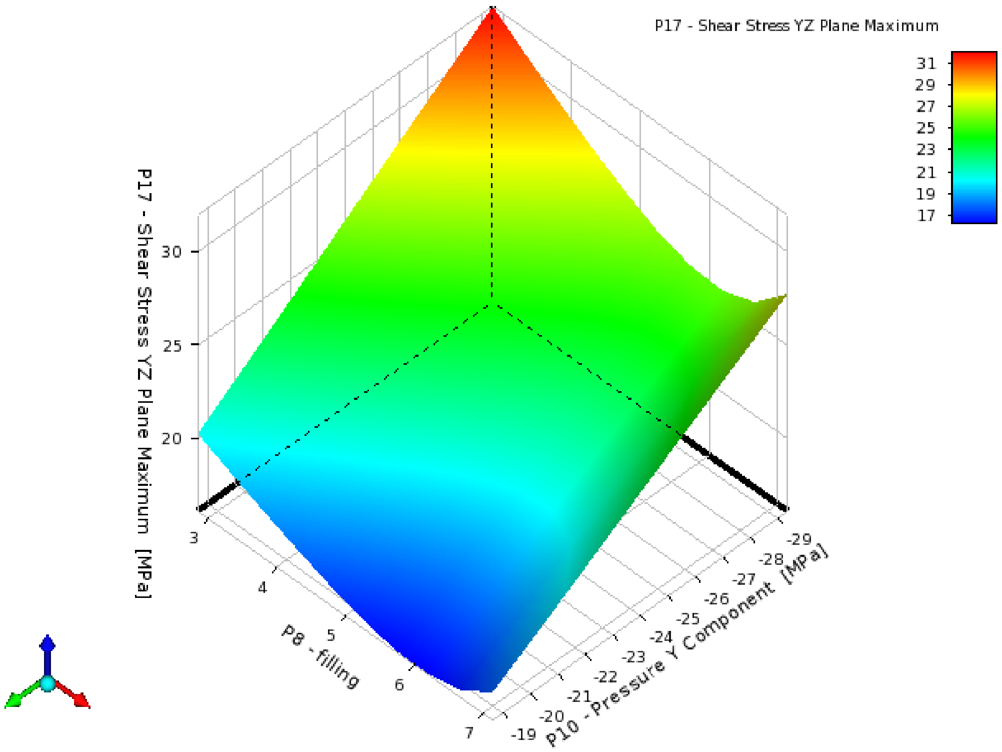

Figure 4: Sinsitivity response chart

4. Filling Stress-Life Analysis

Stress-life method is used to estimate the faigue life of the filling model. For this purpose, the S-N curve of the filling shown in Fig. 5 is used in conjunction with the stress results. Table 5 lists life values for the applied stress. As an example, for an assumed daily loading of 2000 cycles, and using Table 5, 10^7 total life-time cycles divided by 2000 daily cycles is equal to 5000 days, or 13.7 years. This is the approximate life span of the dental amalgam filling, which is only 7% away from previous studies performed by [Animated-teeth, 2015].

5. Filling Reliability Simulation

Reliability is the probability that a structure will last a specified time under specified conditions. Mean time to failure (MTTF) is the mean time to the first failure under specifiedconditions.The results of the filling fatigue life are represented in the histogram shown in Fig. 6. Using the information in this figure, the Probability Density Function (PDF) and the Cumulative Distribution Function (CDF) of the reliability can be drawn.

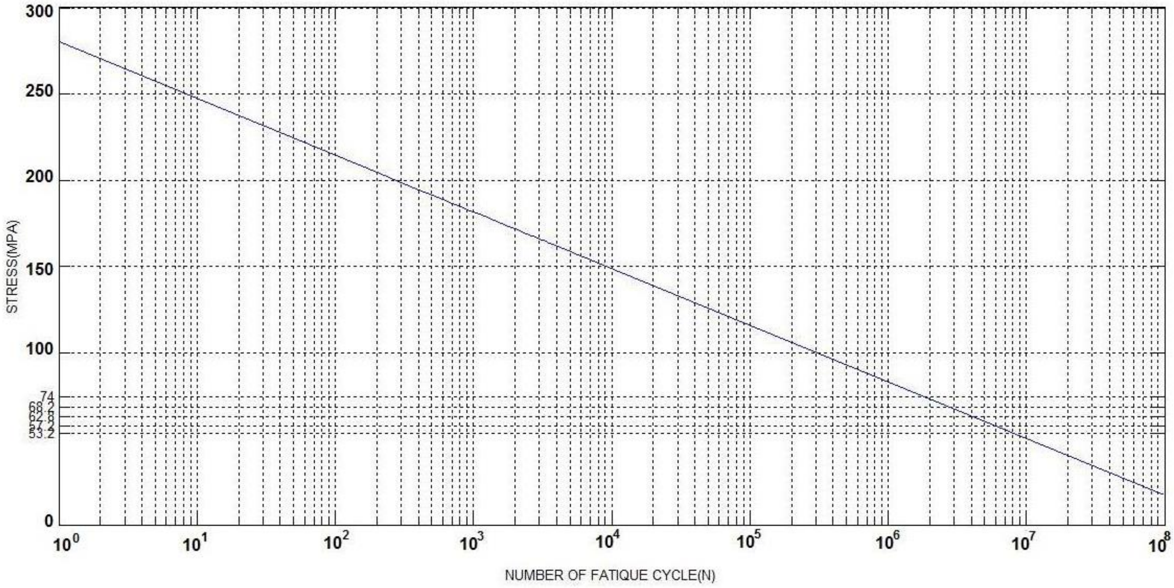

Figure 5: Filling S/N Curve

Table 5: Number of cycles for different stress levels

Stress (MPa)	**No. of Cycles**
48	10^7
42	1.8×10^7
39.4	2×10^7
32.8	3×10^7
29.2	4×10^7
62	4×10^6
54	7×10^6
50	10^7
44.4	1.5×10^7
38.4	2×10^7
74	2×10^6
68.2	3×10^6
62.8	4×10^6
57.2	6×10^6
53.2	8×10^6

6. Filling Reliability Simulation

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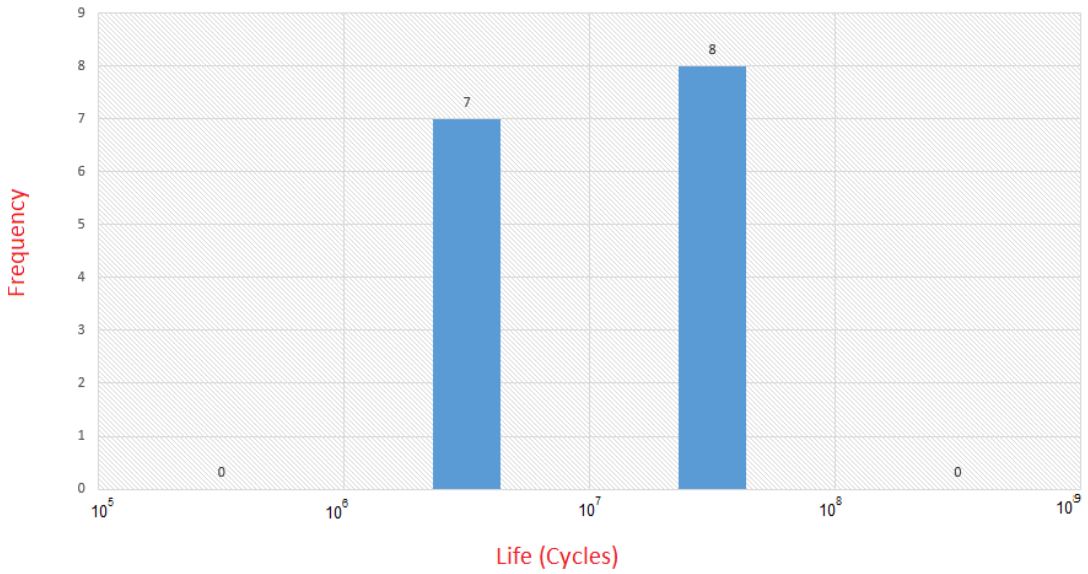

Figure 6: Filling life histogram

The reliability data in this example can be described using Weibull distribution. The PDF for this distribution is defined as:

$$PDF: f(x; a, b) = (a/b^a) \times (x^{a-1}) \times e^{-(\frac{x}{b})^a} \quad (1)$$

Where "x" is the life value, "a" is "scale parameter" and "b" is "shape parameter". By integratingthe PDF in eqn. 1, the Weibull CDF is obtained as:

$$CDF: f(x; a, b) = 1 - e^{-(\frac{x}{b})^a} \quad (2)$$

The resulting filling life PDF and CDF are shown in Fig. 7 and Fig. 8 respectivily.

Since eqn. 2 represents the probability of failure, the reliability "R" is:

$$R = 1 - CDF = e^{-(\frac{x}{b})^a} \quad (3)$$

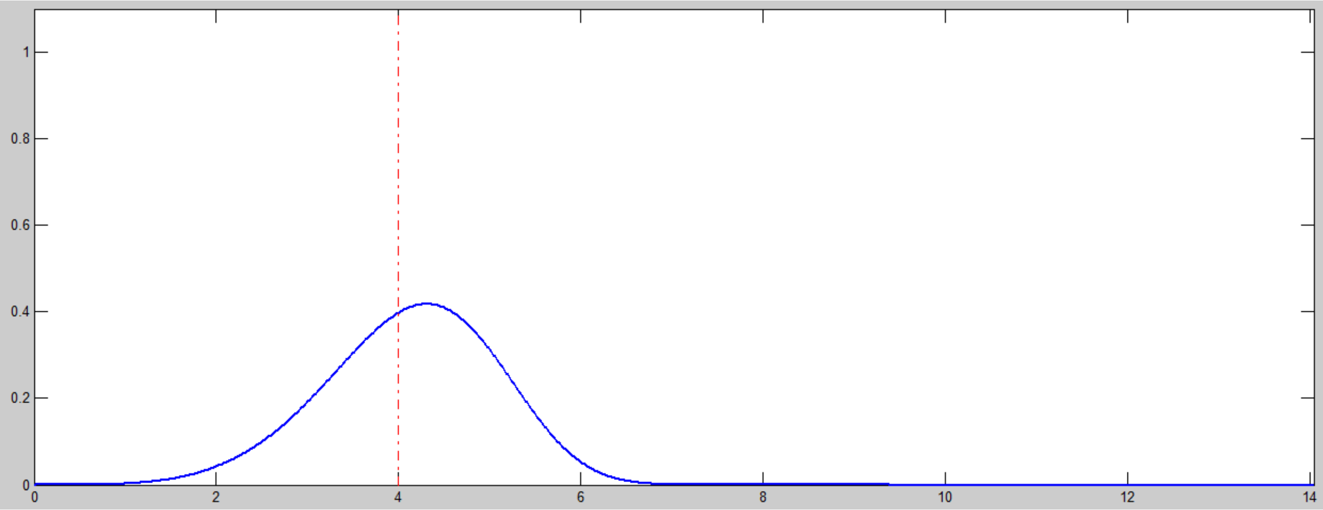

Figure 7: Filling life PDF

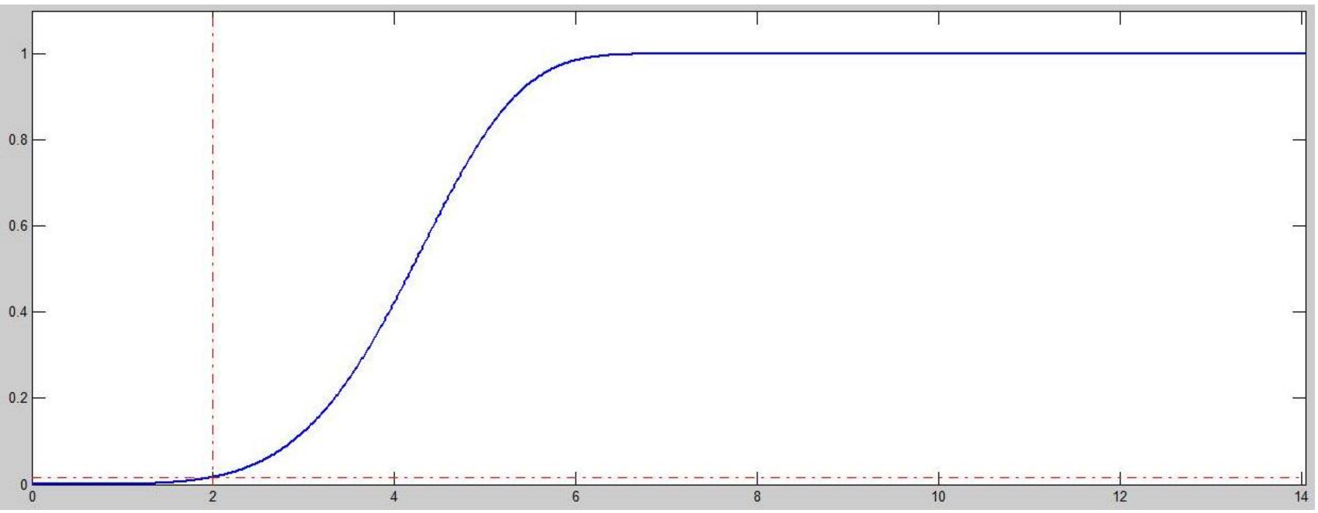

Figure 8: Filling life CDF

Table 6 shows the reliability results versus different values of filling life. The reliability values in the table are calculated using eqn. (3). The data in Table 6 are plotted in Fig. 9. The reliability values can be directly read from Fig. 9 for any value of filling life.

Table 6: Reliability for different life values

No.	Life (Cycles)	Probability of Failure (%)	Reliability (%)
0	10^5	0	100
1	50^5	0.054	99.9
2	100^5	1.7	98.3
3	500^5	12.3	87.7
4	$1,000^5$	45.9	54.1
5	$5,000^5$	81.6	18.4
6	$10,000^5$	98.5	1.5
7	$50,000^5$	99.9	0.1
8	$100,000^5$	100	0

Figure 9: Filling reliability vs. life

6. Discussion and Conclusion

The expected life of a dental amalgam filling is found to be between 10^6 and 10^8 cycles. This is in agreement with previous work. By converting this life duration into years, the average life span of the filling is approximately 12-13 years. The final reliability result shown in Fig. 9 is an excellent tool to determine the expected life of the filling under investigation. We can find how reliable will the filling be after a given life span. On the other hand, for a given reliability level, we can find the expected life span of the filling. A sinsitivity study revealed that, in terms of reliability, the filling depth has an optimum value of 6 mm. However, other factors do affect the depth of the filling such as the extent of tooth decay.

The proposed reliability estimation tool can be used to simulate the reliability of any filling material simply by changing the properties of the filling in the FEM simulation program, then following the same numerical steps shown earlier. Moreover, the tool can be helpful in designing new fillings; By reducing the time and cost required to develop and test the new design or material. Actual models can only be introduced after the success of their reliability models. That means all necessary modifications can be easily accomodated during the simualtion phase.The proposed tool can be further expanded by adding other life prediction methods such as strain-life or crack growth methods.

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