CHAPTER (5)
TEST RESULTS

5.1 Introduction

This chapter presents the results obtained from testing thick-walled woven-roving GFRE tubes with specifications and loading conditions mentioned before. The test results obtained are classified into two groups:

1. Static tests, which include static bending, static torsion and static internal pressure (open and closed tubes).

2. Fatigue tests, which include pure bending, pure torsion and combined bending and internal pressure tests.

It is important to note that, in order to avoid any misleading data, the odd results were rejected and only the specimens that had their failure features within the accepted gauge section, the middle third of the whole length, were considered; which those that seemed to have their failure due to any gripping problems were excluded. Each experimental data point was obtained by considering the average of three specimens tested under the same conditions, and the minimum number of points used to construct S-N curves was 8 data points.

5.2 Static Tests

5.2.1 Pure Bending and Pure Torsion static Tests

Static bending and torsional tests were performed on specimens with two different fiber orientations, $[0,90°]_{3s}$ and $[\pm45°]_{3s}$. Two manufacturing methods for each orientation were used. This group of tests had two targets, the first target was finding out the ultimate global bending strength (S_u) and ultimate global shear strengths (S_{us}) for the materials used respectively when the specimens were dry. It should be noted that, the local static strength in the fiber direction $[F_{1s}]$ is equal to the ultimate global bending strength of the $[0,90°]_{3s}$ specimens, and the local static shear strength in the fiber direction $[F_{6s}]$ is equal to the ultimate global shear strength of the $[0,90°]_{3s}$ specimens [88].

The second target of static bending and torsional tests was to study the effect of fiber oil absorption on the ultimate bending and shear strength. The specimens were filled with the filling media (hydraulic oil ' Mobil DTE 26') with properties as given in Table A3.1, for

about two days. This time was selected according to the maximum number cycles in fatigue tests (N = 10^6 cycle, i.e. $\cong$ 44 hours), then remove the filling oil from the test specimens before the static bending and torsional tests were done. Table 5.1 gives the experimental results of static tests specimens.

Table 5.1: Static bending and torsional tests

Fiber Orientation	Method of Manufacturing	Ultimate bending Strength S_u (MPa)		Ultimate shear Strength S_{us} (MPa)	
		Dry	Wet	Dry	Wet
$[0,90°]_{3s}$	M_1	182	182	69.5	69.5
		137^*	------	47^*	------
		137^{**}	------	64^{**}	------
		135^{***}	------	50^{***}	------
	M_2	198	195.8	24	23.5
$[\pm45°]_{3s}$	M_1	159	159	84	84
		------	------	76^*	------
		118^{**}	------	76^{**}	------
		115^{***}	------	75^{***}	------
	M_2	173	172	35	34.3

Where: M_1 and M_2: The first and the second method of manufacturing respectively

*****Data adapted from Nasr M. A [84], **Data adapted from El-hadary M. M [87], ***Data adapted from Mohamed Y. S [88],***

5.2.2 Internal Pressure Tests

In this section, the hydrostatic internal pressure test results for all the test specimens of both fiber orientations, *[0,90^c]$_{3s}$* and *[±45^c]$_{3s}$* with two methods of manufacturing are presented.

Twenty four internal pressure tests were applied on thick-walled woven-roving Glass fiber reinforced epoxy *(GFRE)* tubes to configuration closed or open tubes. The test results for this group are given in Table 5.2. It is important to note that the tests were recorded to be successful if bursting was achieved, resulting in a sudden decrease in internal pressure.

Table 5.2: Static Pressure tests

Fiber Orientation	Method of Manufacturing	Closed Cylinder			Open Cylinder	
		Burst Pressure $P_{i_{max}}$ (bar)	$\sigma_{H_{max}}$ (MPa)	σ_l (MPa)	Burst Pressure $P_{i_{max}}$ (bar)	$\sigma_{H_{max}}$ (MPa)
[0,90°]₃ₛ	M₁	55	30.6	11.8	65	36
		17.4[*]	271.87[*]	135.9[*]	-----	-----
		122[**]	152.5[**]	76.25[**]	-----	-----
		17.4[***]	271.87[***]	135.9[***]	-----	-----
	M₂	91.667	35.5	12.67	115	46.7
[±45°]₃ₛ	M₁	69.667	35.8	14.3	84	47.3
		56.6[*]	884.37[*]	442.1[*]	-----	-----
		140[**]	175[**]	87.5[**]	-----	-----
		108[***]	1687.5[***]	843.7[***]	-----	-----
	M₂	112	47	16.2	153.667	61.5

Where: M₁ and M₂: The first and the second method of manufacturing respectively

[*]**Data adapted from Önder A. [8], Table A3.81,**

[**]**Data adapted from Tolga L. [52], Table A3.82.**

[***]**Data adapted from Erkal S. [148], Table A3.84.**

5.3 Fatigue Tests

All specimens were tested under ambient conditions and constant frequency of 6.33 Hz. The data points were used to plot the corresponding S-N curves on semi-log scale, being fitted using the power law: $max. stress = aN^b$

The fatigue test results were divided into two main groups:

1. The first group of the fatigue test results contains the results of completely reversed pure bending and completely reversed pure torsion tests.

2. The second includes the results of combined completely reversed bending and internal pressure tests.

5.3.1 The first group

5.3.1.1 Completely reversed Pure bending fatigue test

Tests were performed on both fiber orientations, *[0,90ᶜ]₃ₛ* and *[±45ᶜ]₃ₛ* , with two methods of manufacturing for each orientation and the pressure ratio (P_r =0) . All specimens were tested under completely reversed pure bending, (R = -1) and the pressure ratio (P_r =0), i.e. no pressure inside the specimens in this test. This group of tests had two

targets, the first is that, in order to find out the bending fatigue strength (S_f) which represents the local fatigue strength in the fiber direction (F_{1f}), it is important to note that, the global fatigue bending strength of the $[0,90°]_{3s}$ tubes is considered as local fatigue strength of *GFRE* in the fiber direction [F_1]. The second target is to study the effect of fiber orientation and specimens manufacturing methods on the fatigue behavior of the *GFRE* under pure bending stress.

The S-N curves for this group are shown in Figures 5.1 to 5.4, the two constants (a) and (b), of the used power law: $\sigma_{max} = aN^b$ were found to have the values in Table 5.3. Tables A3.5 to A3.12 (Appendix (3)) give the data of completely reversed pure bending tests.
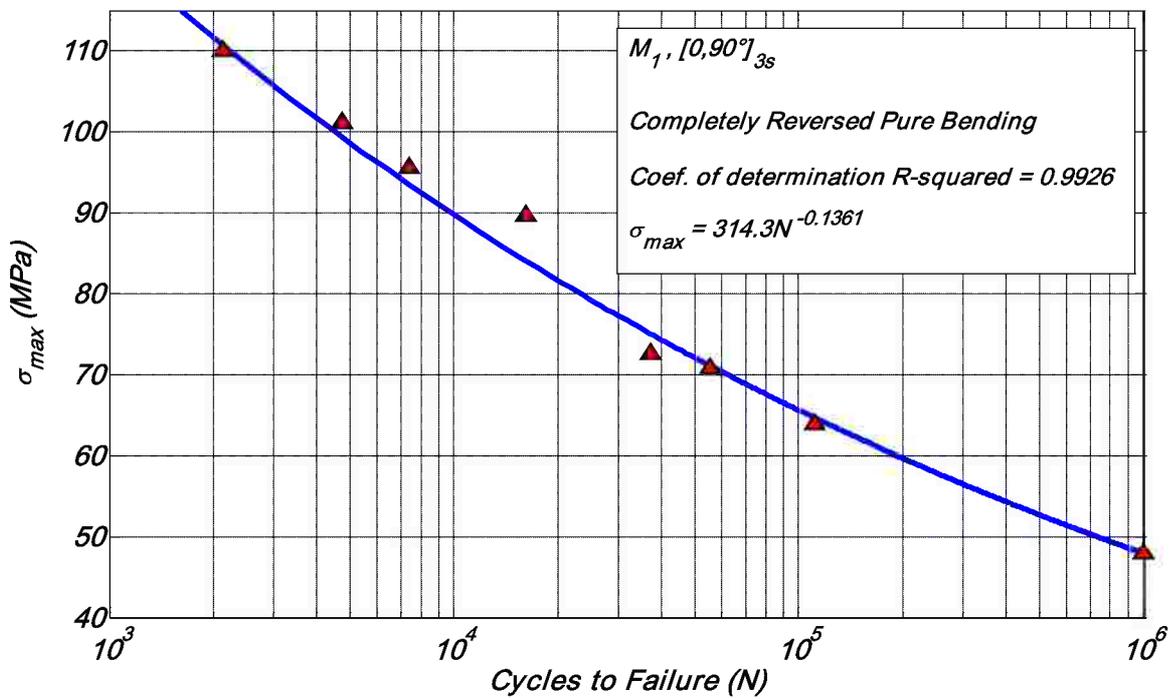
Figure 5.1 Completely Reversed Pure Bending of M_1, $[0,90°]_{3s}$ specimens Under $P_r = 0$
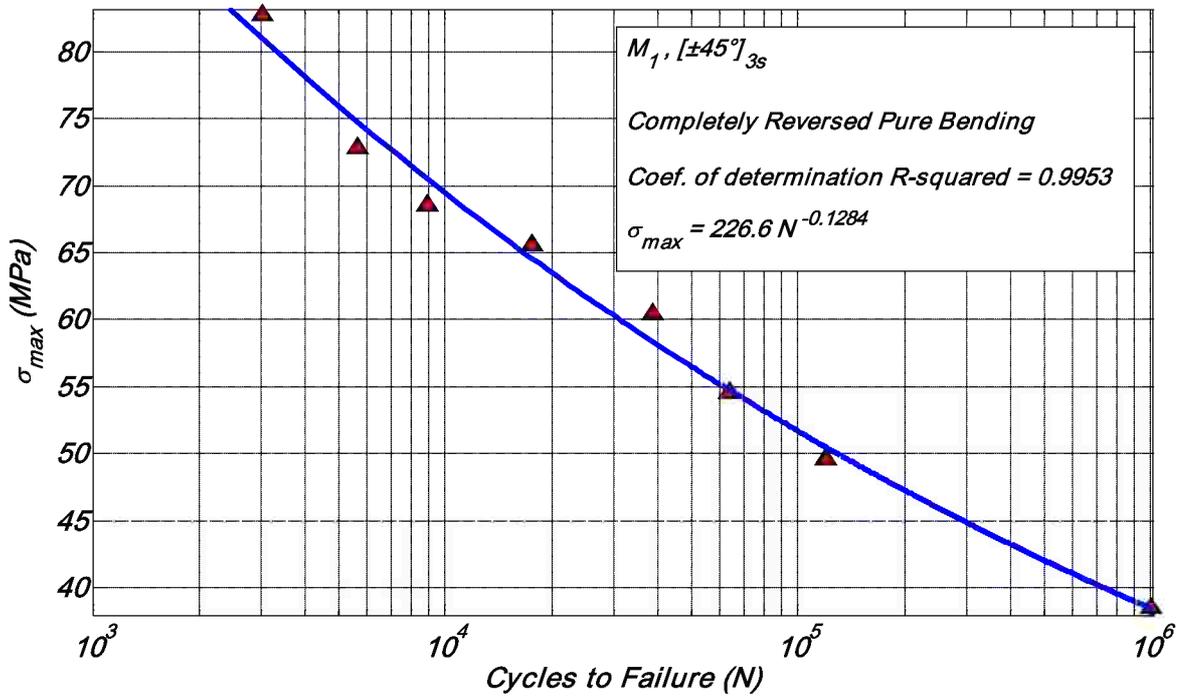
Figure 5.2 Completely Reversed Pure Bending of M_1, $[\pm 45°]_{3s}$ specimens Under $P_r = 0$
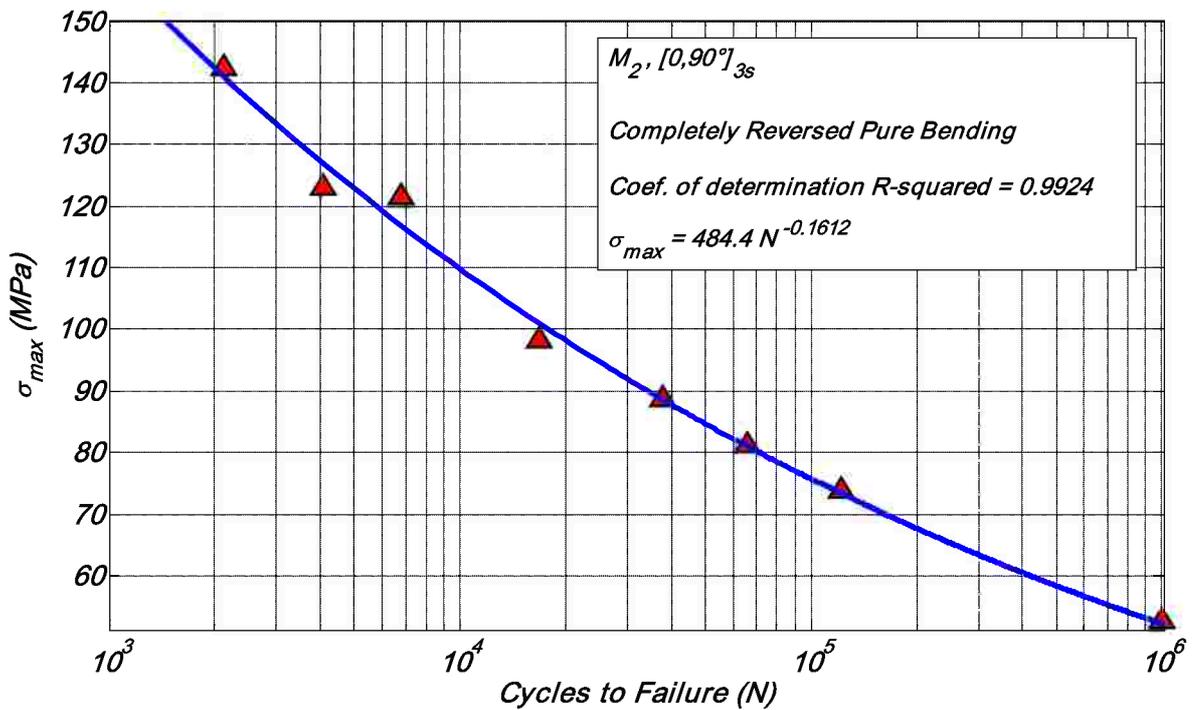
Figure 5.3 Completely Reversed Pure Bending of M_2, $[0,90°]_{3s}$ specimens Under $P_r = 0$
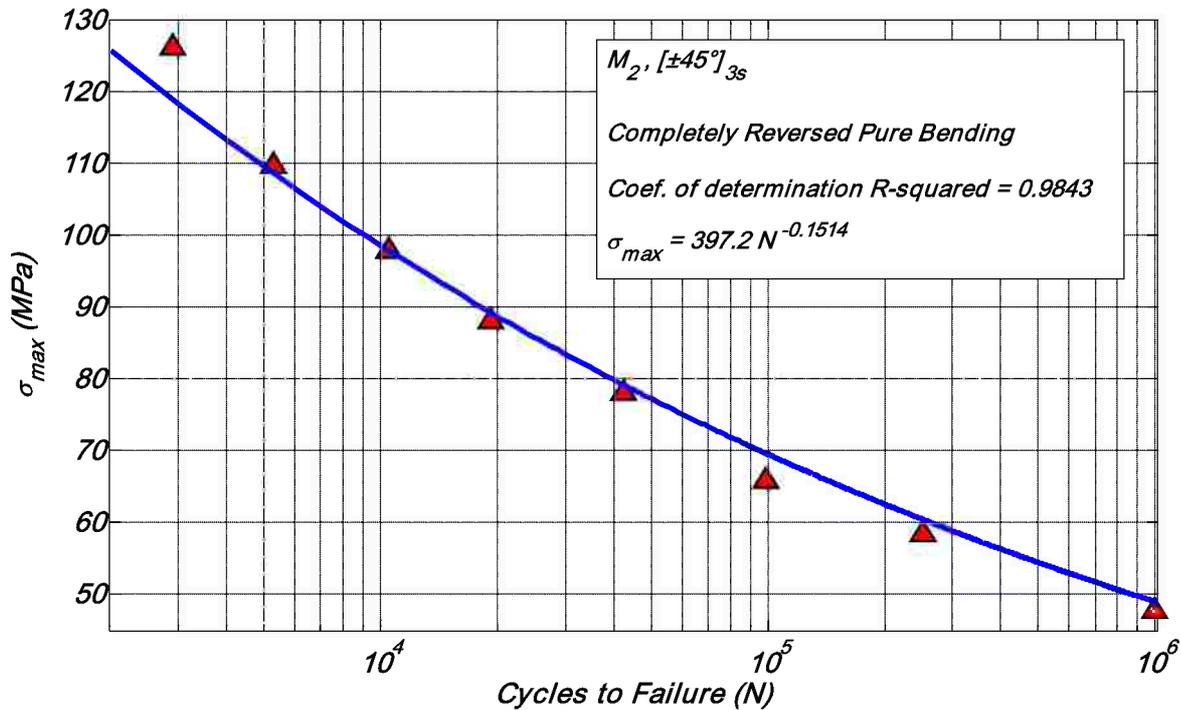
Figure 5.4 Completely Reversed Pure Bending of M_2, $[\pm 45°]_{3s}$ specimens Under $P_r = 0$

Table 5.3: Fatigue Constants (a) and (b) for Completely Reversed Pure Bending Under $P_r = 0$

Fiber orientation	Method of Manufacturing	a (MPa)	b	Correlation factor
$[0,90°]_{3s}$	M_1	314.3	-0.1361	0.9926
		172.47[*]	-0.1152[*]	0.99568[*]
		177.94[**]	-0.1152[**]	0.976936[**]
		179.017[***]	-0.11384[***]	0.99036[***]
	M_2	484.4	-0.1612	0.9924
$[\pm 45°]_{3s}$	M_1	226.6	-0.1284	0.9953
		118.87[**]	-0.088[**]	0.97[**]
		117.822[***]	0.0973[***]	0.98533[***]
	M_2	397.2	-0.1514	0.9843

Where: M_1 and M_2: The first and the second method of manufacturing respectively

    [*]*Data adapted from Nasr M. A* [84], [**]*Data adapted from El-hadary M. M* [87],

    [***]*Data adapted from Mohamed Y. S* [88],

5.3.1.2 Pure Torsion fatigue tests

Tests were performed on both fiber orientations, $[0,90^c]_{3s}$ and $[\pm 45^c]_{3s}$, with two methods of manufacturing for each orientation. All specimens were tests under completely reversed pure torsion, (R = -1). Figures 5.5 to 5.8 show the corresponding S-N curves for

all fiber orientations and methods of manufacturing. Also the two constants (c) and (d), of the used power law: $\tau_{max} = cN^d$ were found to have the values in Table 5.4. Tables A3.13 to A3.20, Appendix (3), give the data of completely reversed pure torsion tests.
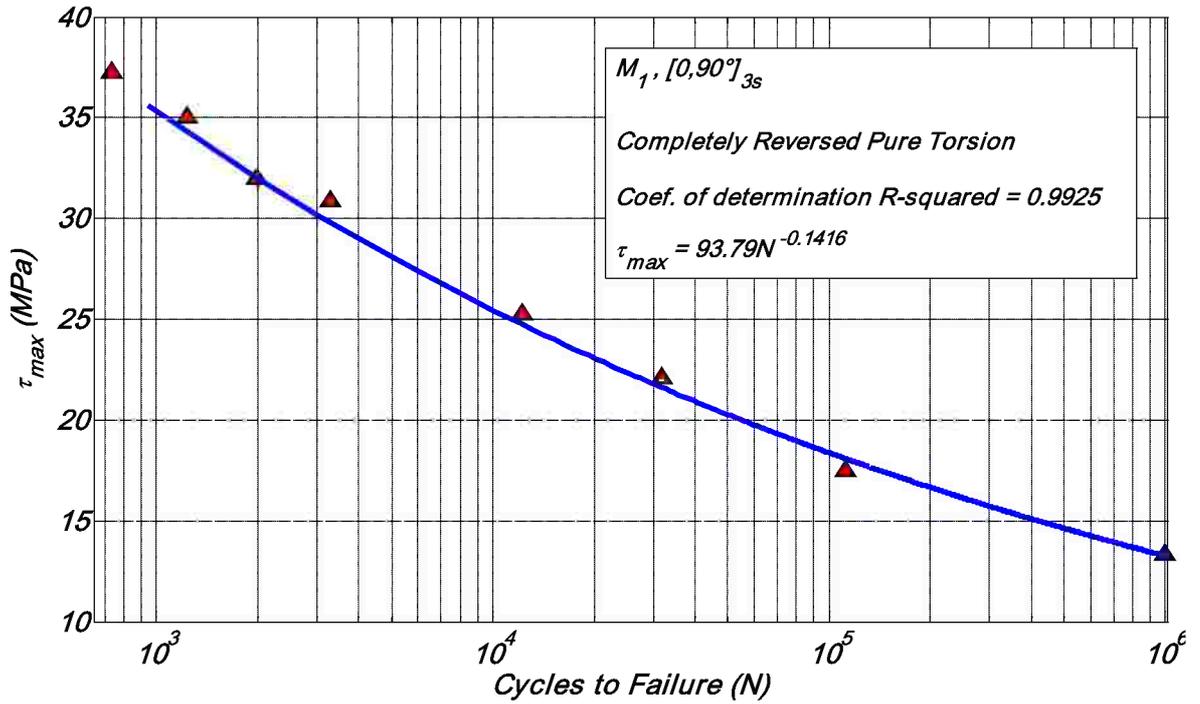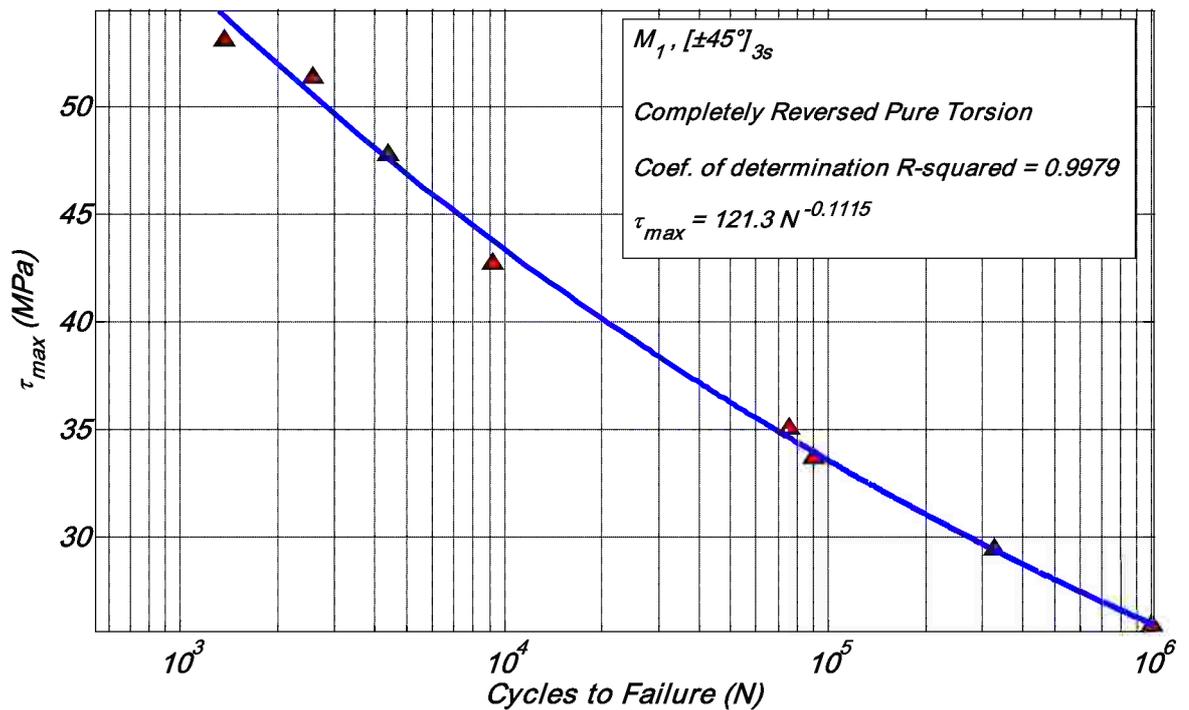

M_1, $[0,90°]_{3s}$

Completely Reversed Pure Torsion

Coef. of determination R-squared = 0.9925

$\tau_{max} = 93.79N^{-0.1416}$

Figure 5.5 Completely Reversed Pure Torsion of M_1, $[0,90°]_{3s}$ specimens

M_1, $[\pm45°]_{3s}$

Completely Reversed Pure Torsion

Coef. of determination R-squared = 0.9979

$\tau_{max} = 121.3\,N^{-0.1115}$

Figure 5.6 Completely Reversed Pure Torsion of M_1, $[\pm45°]_{3s}$ specimens
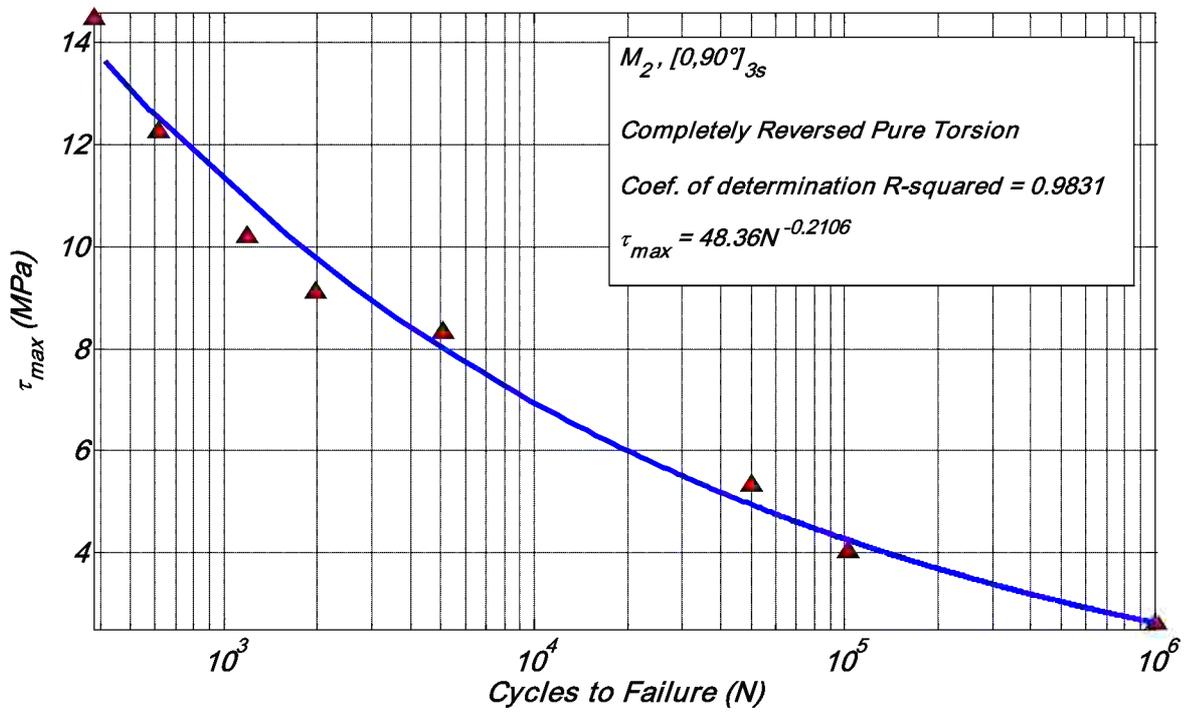
Figure 5.7 Completely Reversed Pure Torsion of M_2, $[0,90°]_{3s}$ specimens
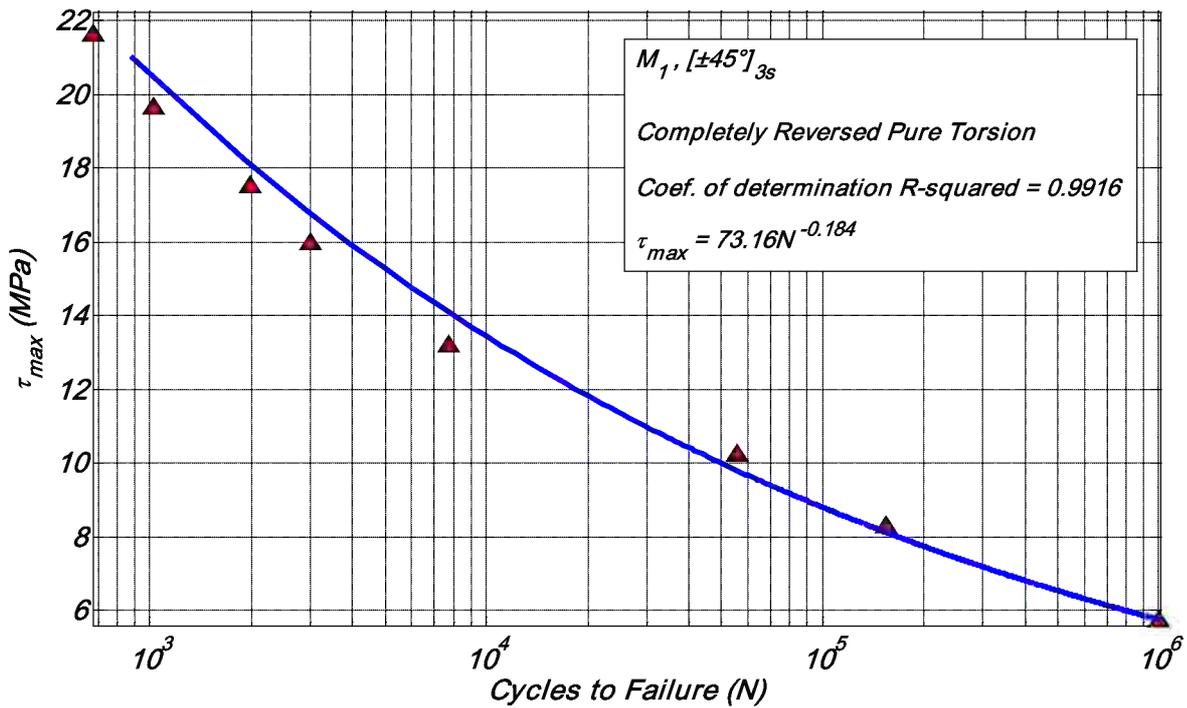
Figure 5.8 Completely Reversed Pure Torsion of M_2, $[\pm 45°]_{3s}$ specimens

Table 5.4: Fatigue Constants (c) and (d) for Completely Reversed Pure Torsion

Fiber orientation	Method of Manufacturing	c (MPa)	d	Correlation factor
$[0,90°]_{3s}$	M_1	93.79	-0.1416	0.9925
		60.9202[*]	-0.120095[*]	0.954031[*]
		62.388[**]	-0.1234[**]	0.982583[**]
		61.1568[***]	-0.1244[***]	0.984878[***]
	M_2	48.36	-0.2106	0.9831
$[\pm45°]_{3s}$	M_1	121.3	-0.1115	0.9979
		103.885[*]	-0.130215[*]	0.989443[*]
		110.348[**]	-0.1227[**]	0.968783[**]
		100.664[***]	-0.114243[***]	0.965949[***]
	M_2	73.16	-0.184	0.9916

Where: M_1 and M_2: The first and the second method of manufacturing respectively

[*]***Data adapted from Nasr M. A [84],*** [**]***Data adapted from El-hadary M. M [87],***

[***]***Data adapted from Mohamed Y. S [88],***

5.3.2 The second group

5.3.2.1 The combined completely reversed bending and internal pressure

Tests were done on both fiber orientations, *[0,90°]₃ₛ* and *[±45°]₃ₛ*, with two methods of manufacturing for each orientation. All specimens were tested under completely reversed pure bending, (R = -1) and internal pressure with different pressure ratios between the applied pressure and burst pressure ($P_r = P/P_{max} = 0, 0.25, 0.5, 0.75$), where P_{max} is the burst pressure, Table 5.2, according to the fiber orientation and the method of manufacturing. According to the results given in Table 5.2 , the worst condition occurred when the closed tube specimens was used (i.e. the pipe line valve was closed during the test), so all results in this section represent the fatigue test results of combined bending and internal pressure for closed tube specimens.

Figures 5.9 to 5.20 show the S-N curves for this group of tests. Also the two constants (a) and (b), of the used power law: $\sigma_{max} = aN^b$ were found to have the values given in Tables 5.5 to 5.7. Tables A3.43 to A3.54, Appendix (3), give the test data for this group.
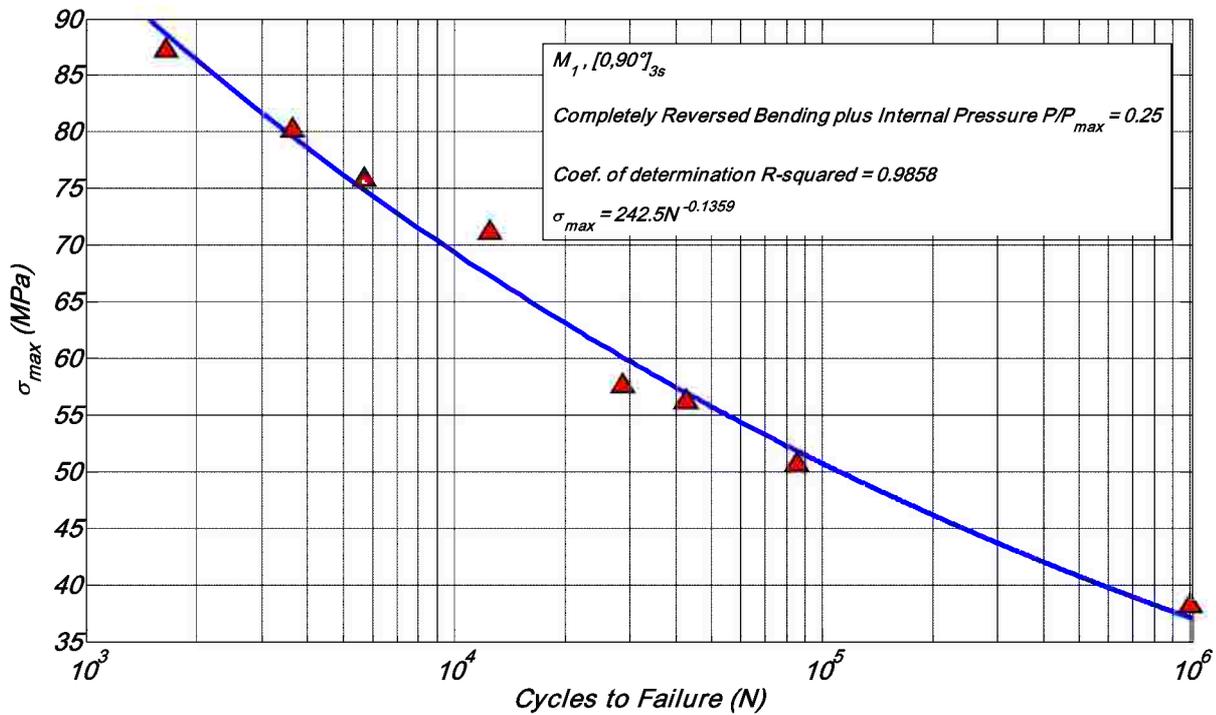
Figure 5.9 Completely Reversed Bending plus Internal Pressure of M_1, $[0,90°]_{3s}$
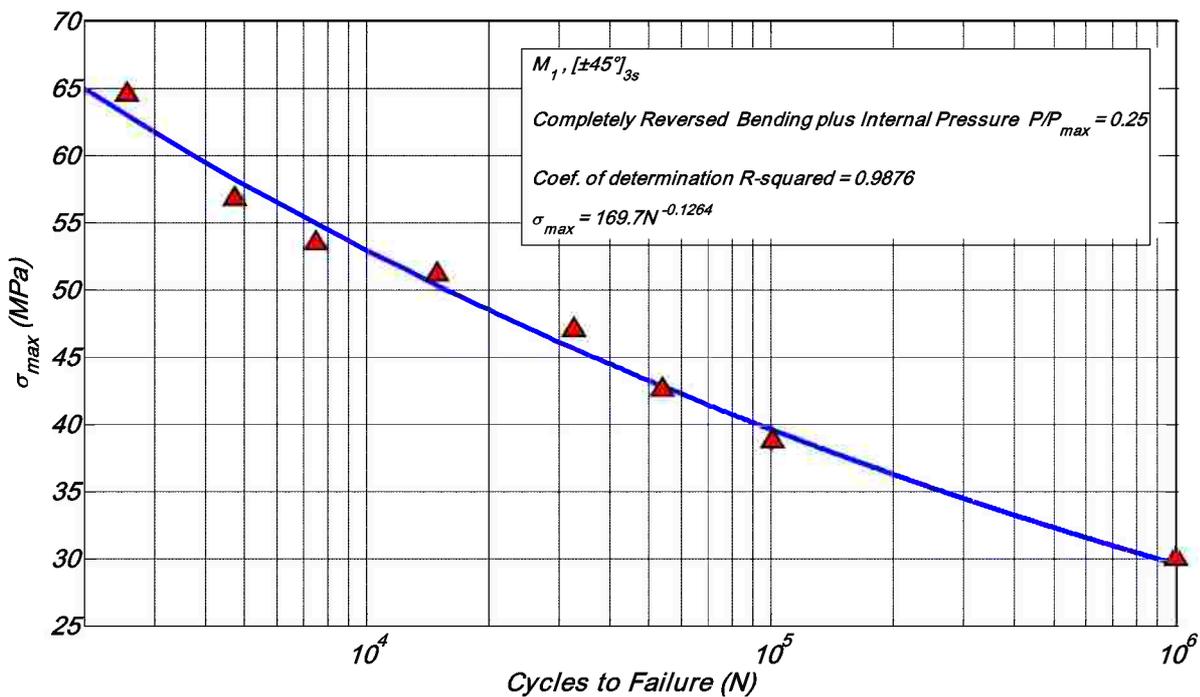specimens with $P_r = 0.25$

Figure 5.10 Completely Reversed Bending plus Internal Pressure of M_1, $[\pm45°]_{3s}$
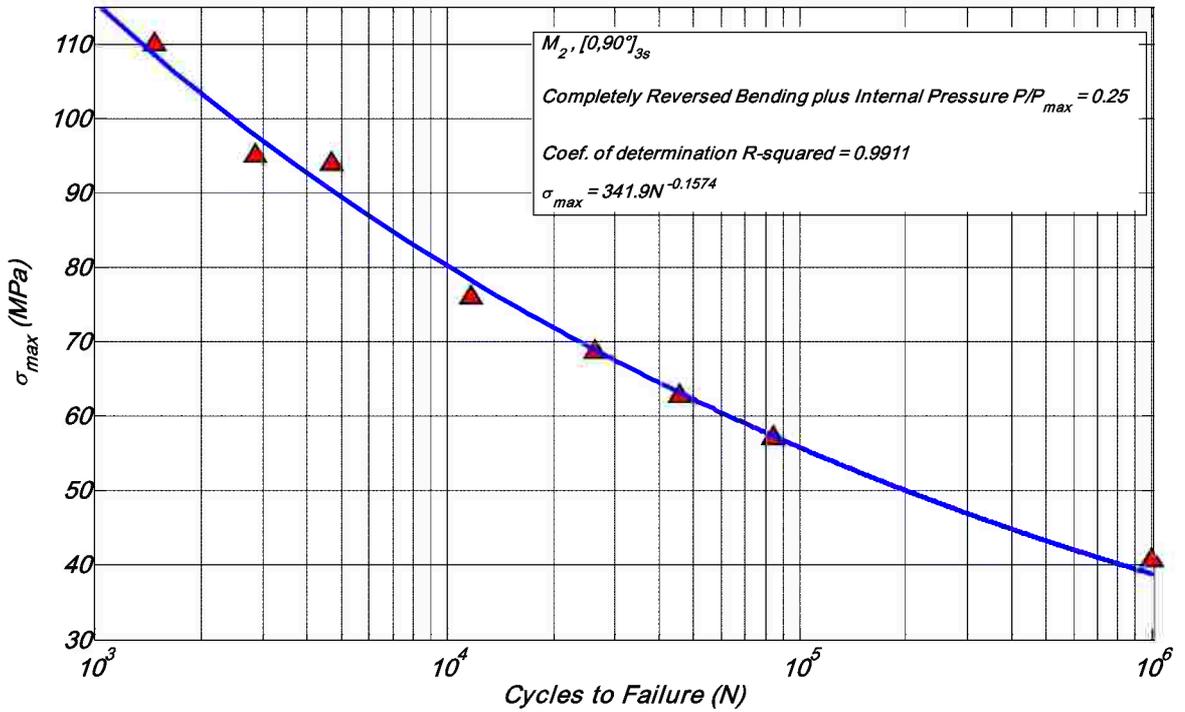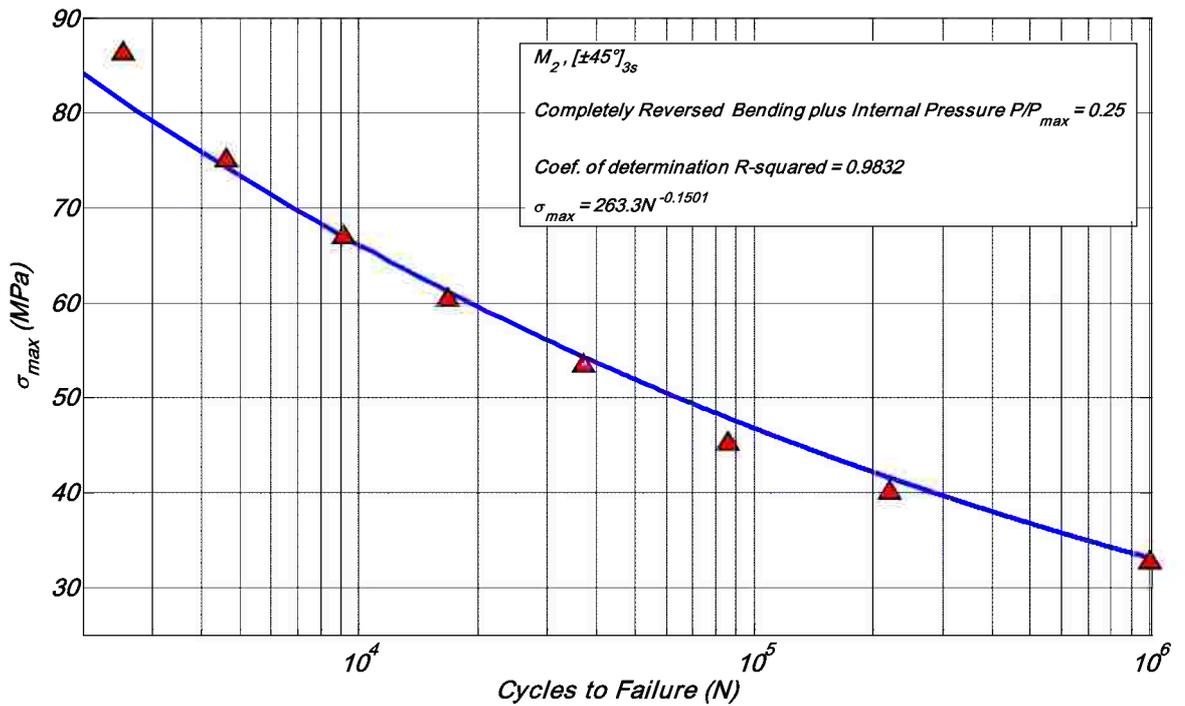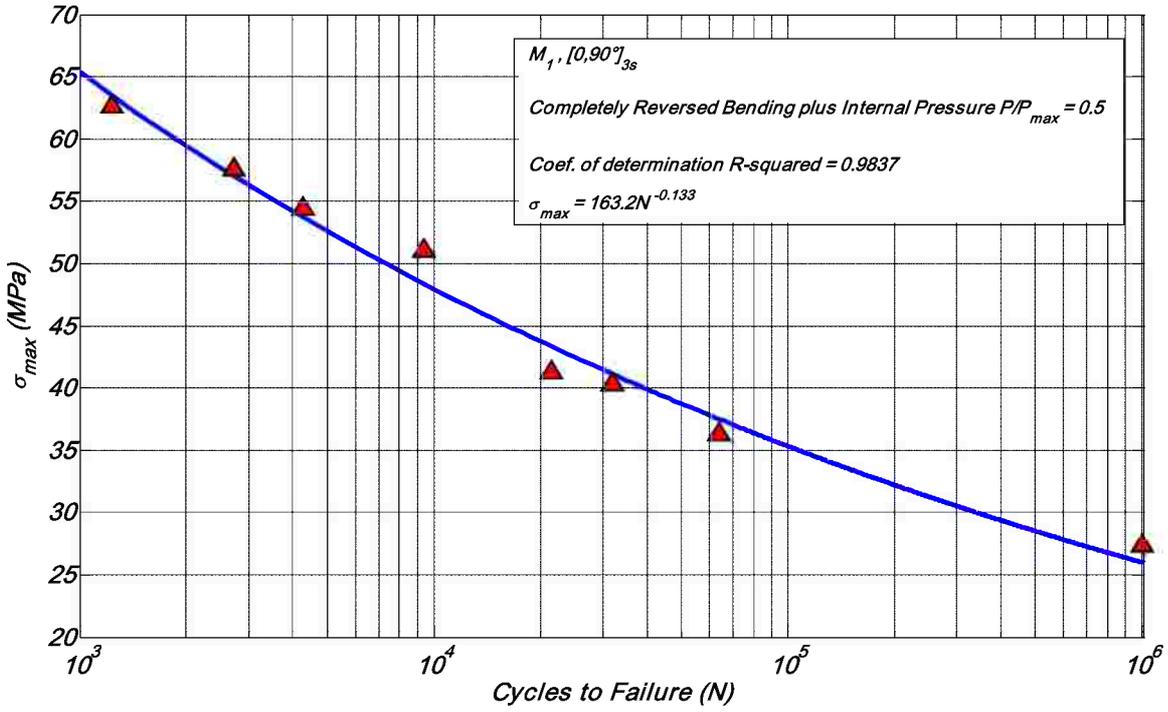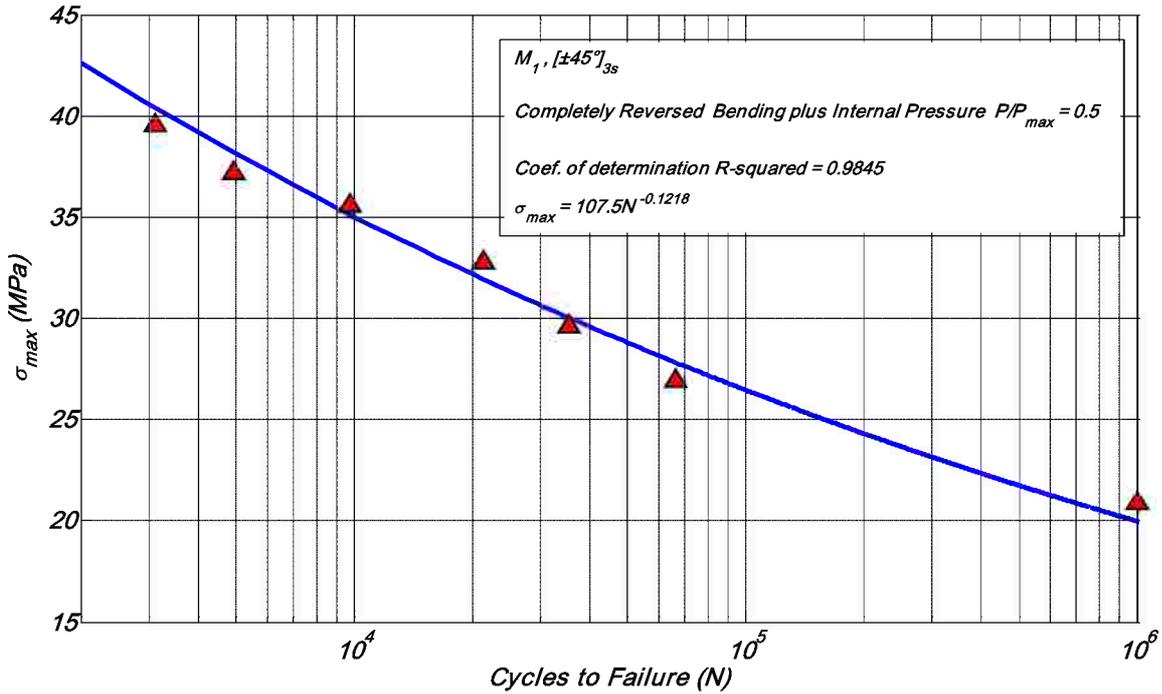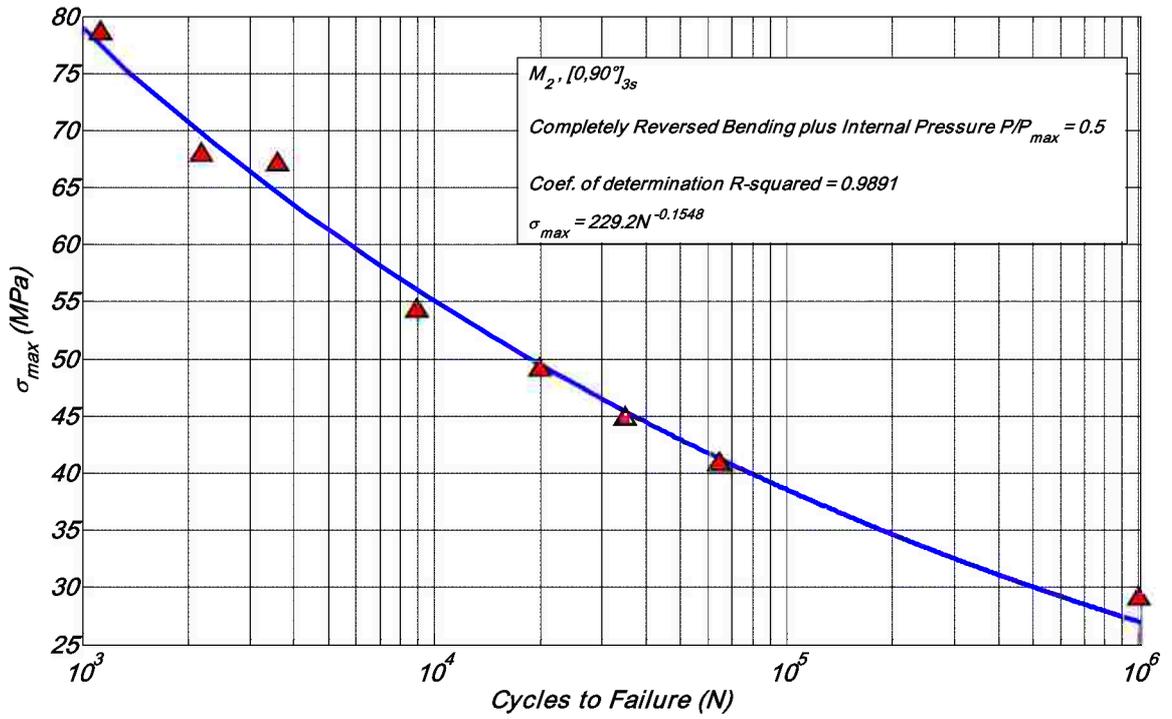specimens with $P_r = 0.25$

Figure 5.11 Completely Reversed Bending plus Internal Pressure of M$_2$, [0,90°]$_{3s}$ specimens with P$_r$ = 0.25

Figure 5.12 Completely Reversed Bending plus Internal Pressure of M$_2$, [±45°]$_{3s}$ specimens with P$_r$ = 0.25

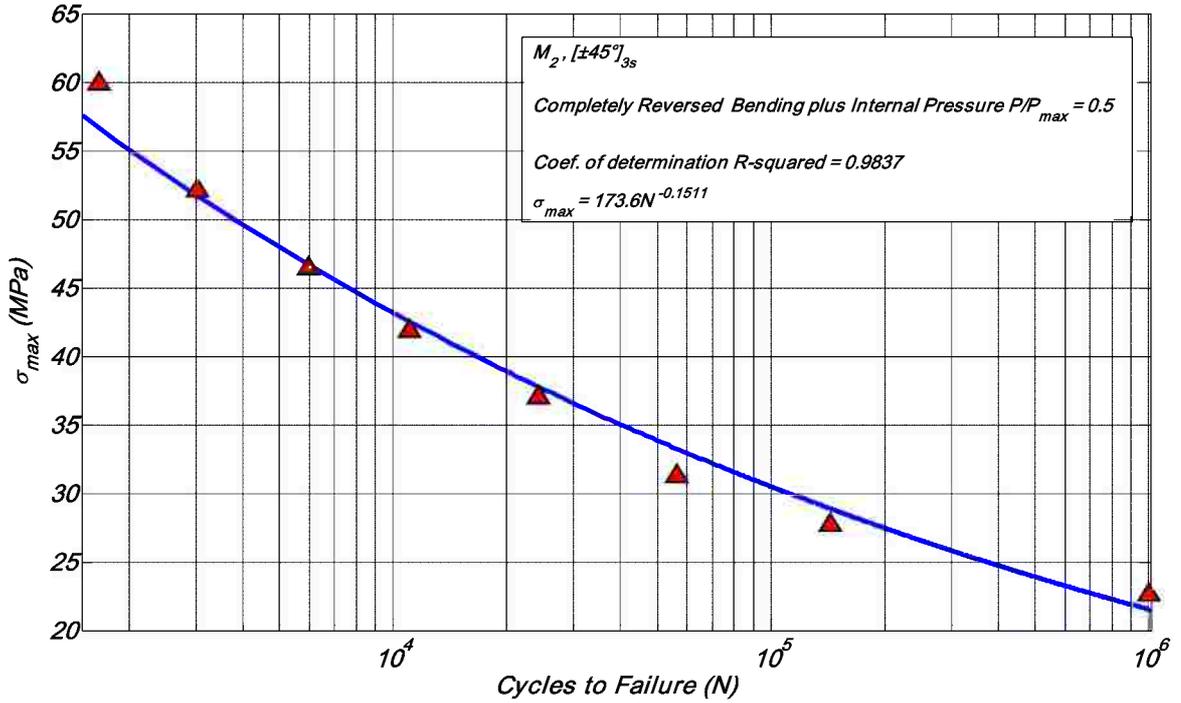Figure 5.13 Completely Reversed Bending plus Internal Pressure of M_1, $[0,90°]_{3s}$ specimens with $P_r = 0.5$

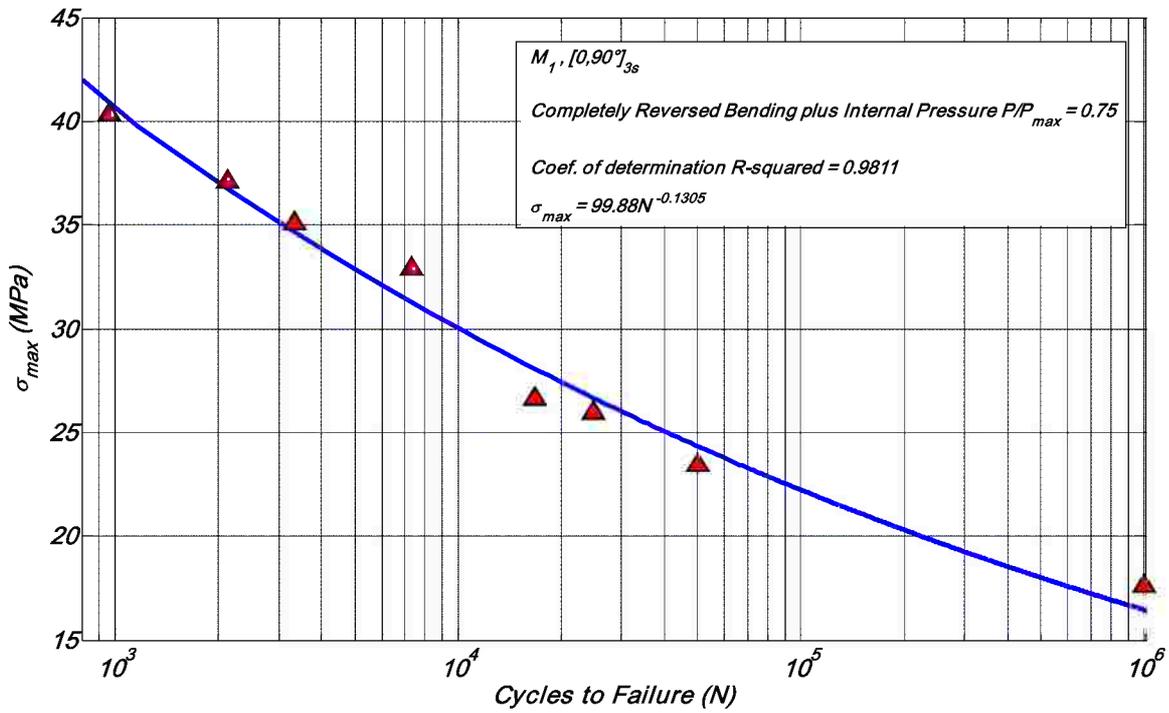Figure 5.14 Completely Reversed Bending plus Internal Pressure of M_1, $[\pm45°]_{3s}$ specimens with $P_r = 0.5$

Figure 5.15 Completely Reversed Bending plus Internal Pressure of M_2, $[0,90°]_{3s}$ specimens with $P_r = 0.5$

Figure 5.16 Completely Reversed Bending plus Internal Pressure of M_2, $[\pm45°]_{3s}$ specimens with $P_r = 0.5$

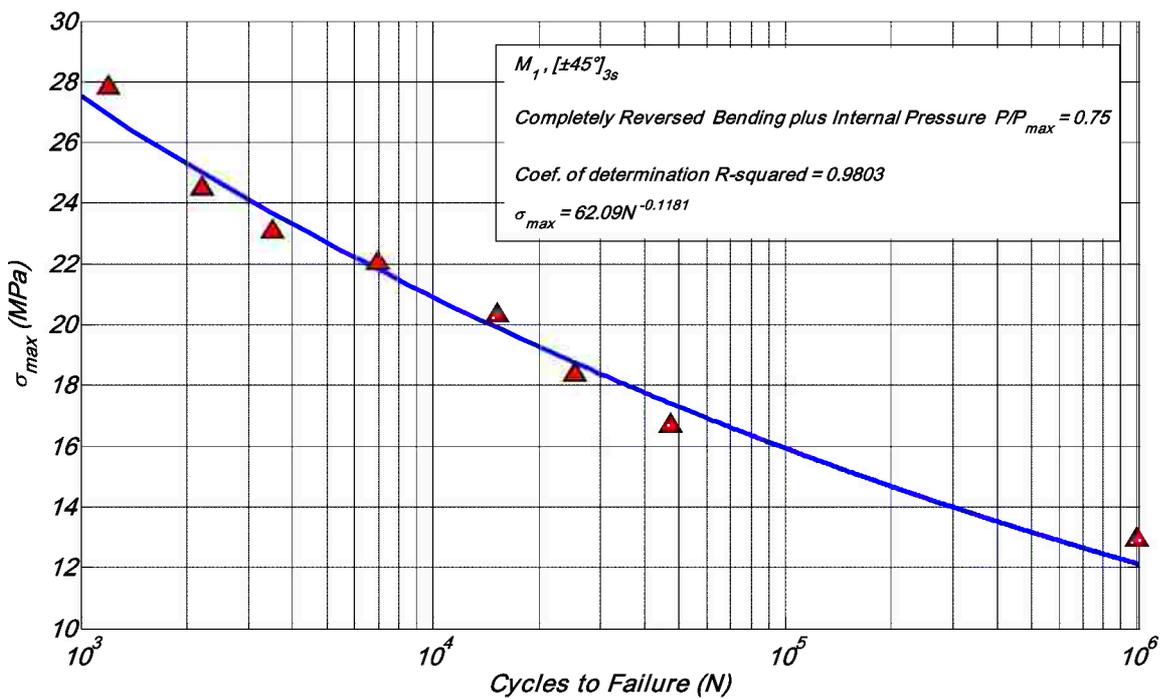Figure 5.17 Completely Reversed Bending plus Internal Pressure of M_1, $[0,90°]_{3s}$ specimens with $P_r = 0.75$

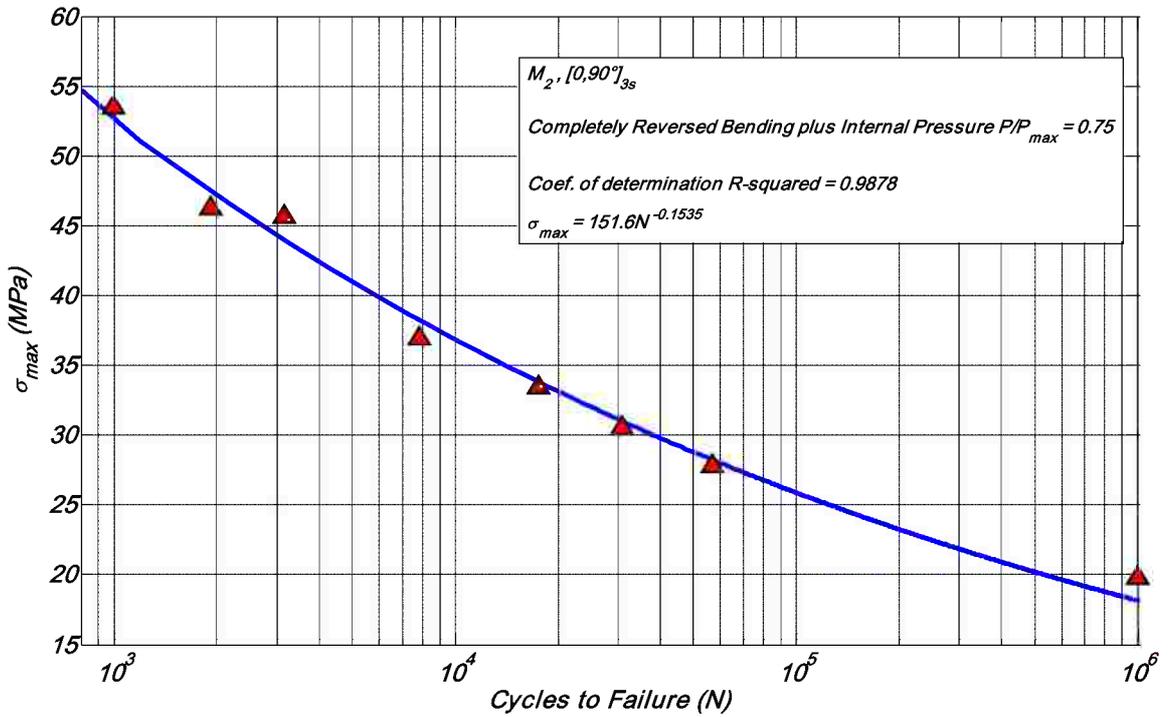Figure 5.18 Completely Reversed Bending plus Internal Pressure of M_1, $[\pm45°]_{3s}$ specimens with $P_r = 0.75$

Figure 5.19 Completely Reversed Bending plus Internal Pressure of M$_2$, [0,90°]$_{3s}$ specimens with P$_r$ = 0.75
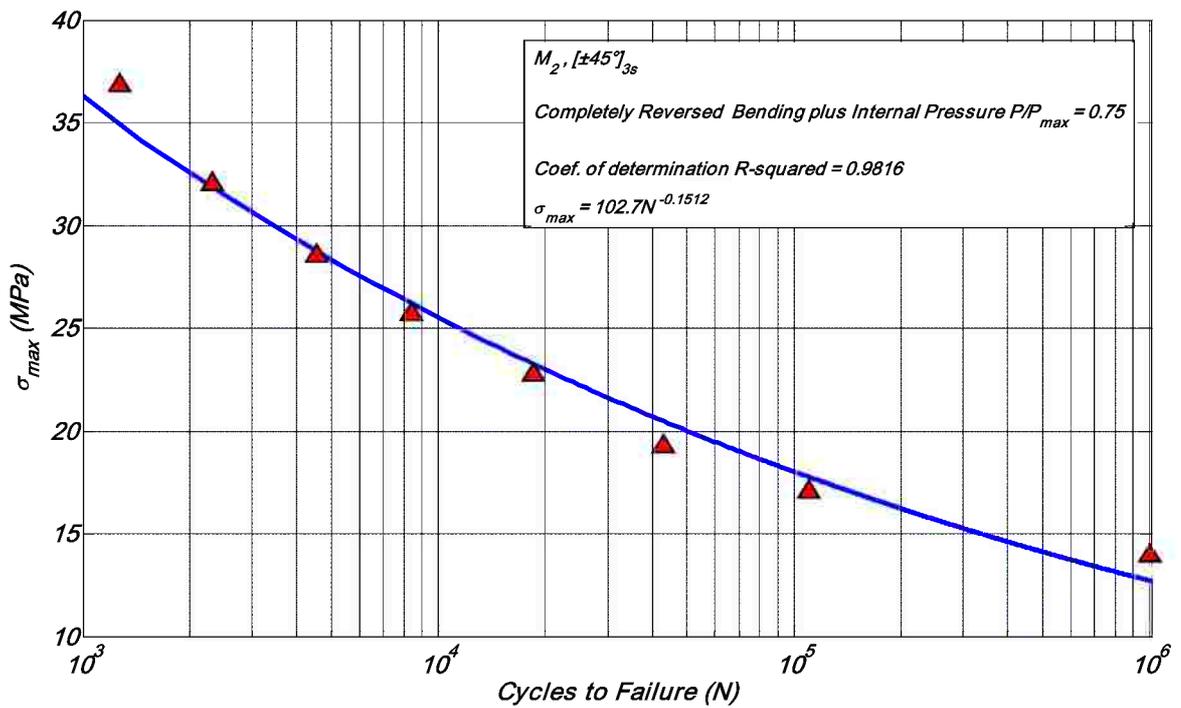

Figure 5.20 Completely Reversed Bending plus Internal Pressure of M$_2$, [±45°]$_{3s}$ specimens with P$_r$ = 0.75

Table 5.5: Fatigue Constants (a) and (b) for Completely Reversed Bending plus Internal Pressure with $P_r = 0.25$

Fiber orientation	Method of Manufacturing	a (MPa)	b	Correlation factor
$[0,90^c]_{3s}$	M_1	242.5	-0.1359	0.9858
	M_2	341.9	-0.1574	0.9911
$[\pm45^c]_{3s}$	M_1	169.7	-0.1264	0.9876
	M_2	263.3	-0.1501	0.9832

Where: M_1: The first method of manufacturing

M_2: The second method of manufacturing

Table 5.6: Fatigue Constants (a) and (b) for Completely Reversed Bending plus Internal Pressure with $P_r = 0.5$

Fiber orientation	Method of Manufacturing	a (MPa)	b	Correlation factor
$[0,90^\circ]_{3s}$	M_1	163.2	-0.133	0.9837
	M_2	229.2	-0.1548	0.9891
$[\pm45^\circ]_{3s}$	M_1	107.5	-0.1218	0.9845
	M_2	173.6	-0.1511	0.9837

Where: M_1: The first method of manufacturing

M_2: The second method of manufacturing

Table 5.7: Fatigue Constants (a) and (b) for Completely Reversed Bending plus Internal Pressure with $P_r = 0.75$

Fiber orientation	Method of Manufacturing	a (MPa)	b	Correlation factor
$[0,90^\circ]_{3s}$	M_1	99.88	-0.1305	0.9811
	M_2	151.6	-0.1535	0.9878
$[\pm45^\circ]_{3s}$	M_1	62.09	-0.1181	0.9803
	M_2	102.7	-0.1512	0.9816

Where: M_1: The first method of manufacturing

M_2: The second method of manufacturing