IMPROVING THE CRUSH RESISTANCE OF SUBMARINE CABLES

Weiwei Shen, Rendong Xu, Guilin Sun, Lei Zhang, Chao Zhang, Yuan Liu, Mingjun Ye, Di Wu, Qinyang Meng, Danjun Cai,Changji Hao(Hengtong Marine Cable Systems)
Email: shenww@htgd.com.cn

Hengtong Marine Cable Systems,
No 8 Tongda Road, Changshu Economic Development Zone,
Jiangsu Province, China 215537

Abstract: Many submarine cable faults are caused by external forces which deform and crush the cable. This paper investigates improvements in cable crush resistance through different Fiber in Metal Tube (FIMT) designs, based on Light Weight (LW) cable and Double Armoured (DA) cable. Finite element models have predicted cable deformations, and these results are compared and analyzed. To verify the finite element models, crush tests have been performed on different FIMT, LW and DA cable structures. Results are presented which show the relative crush resistance improvements and conclusions are made which can be useful to future designs of submarine cable.

1. INTRODUCTION

Submarine cables should be designed to resist the lateral pressure in the process of transportation & installation, and also to withstand the high hydrostatic pressures when laid in the deep sea. How to improve the crush resistance of submarine cables is an important question for submarine cable continuous development.

In the center tube cable, the FIMT is the central element of the submarine cable, so that when the cable is subjected to an external crush force, the fibers obtain very good protection because of their position in the cable structure.[1-5]

Hengtong Marine Cable Systems (HMCS), a professional manufacturer of submarine cables has carried out some research about the crush resistance of submarine cable.

2. INVESTIGATING THE CRUSH RESISTANCE OF CABLES USING FINITE ELEMENT TECHNIQUE

The mechanical strength of the optical fiber and fiber jelly is very low, allowing us to ignore them in the finite element models, as they will have little effect on the cable crush resistance performance.

The cable model has been built along the positive direction of z-axis of the rectangular x, y, z coordinate system. The cable elements modelled include the FIMT steel tube, the inner armouring, the copper conductor and the PE insulation. The Solid 164 element type was chosen to create the cable structure, with the appropriate material properties allocated to each part of the cable model. The cable model has been designed with clamping bodies built on both sides of the cable. The cable clamping bodies have been modelled with a high hardness to simulate a rigid body, and in this way, the clamps can be used to applied load and define constraints easily. The finite element model of crush resistance of submarine cable is shown in Figure 1. The clamp under the cable remains fixed, while the clamp above the cable can move along the negative direction of Y axis, generating a crushing action. [6]

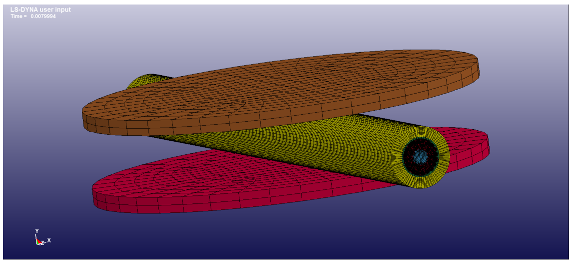


Figure 1. The finite element model

When an initially circular cross section cable is subjected to a crush force, the cable structure will deform causing the cable diameter to decrease in the y axis direction, and to increase in the x-axis direction. If we define the maximum x-axis cable diameter to be *D* and the minimum y-axis cable diameter to be *d*, then the cable *D/d* ratio is a useful way to compare the deformation between the different cables modelled.

Five cable models have been created to investigate the importance of the copper conductor and PE insulation. The structure of cable models are shown in Figure 2 and Table 1.

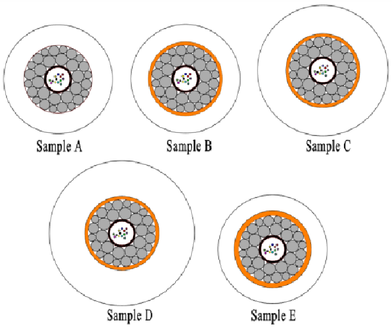


Figure 2. Cable Structures Modelled.

Sample ID	FIMT	Inner Armour	Copper Conductor	PE Insulation
Sample A	Yes	Yes	No	Thin (2.8 mm)
Sample B	Yes	Yes	Yes (0.4mm)	Thin (2.8 mm)
Sample C	Yes	Yes	Yes (0.4mm)	Medium (3.8 mm)
Sample D	Yes	Yes	Yes (0.4mm)	Thick (4.9 mm)
Sample E	Yes	Yes	Yes (0.6mm)	Thin (2.8 mm)

Table 1. Structure of Cable Models

In the cable crush simulation, the same high pressure force was applied to each of these five models to deform the central FIMT. The crush load was selected to deform the cable structures being modelled so that the ratio of *D/d* exceeded 1.15 (chosen as a reasonable level of cable deformation). The finite element models of the deformed cable cross sections are shown in the Figure 3 below during the application of the same maximum force

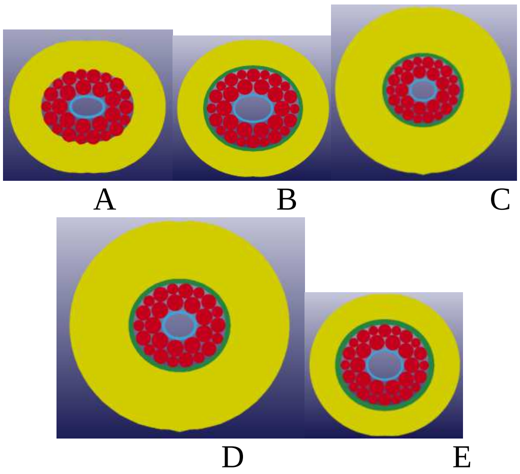


Figure 3. The deformation of different cable models subjected to the same force

To compare the different levels of cable deformation sustained, the ratio of *D/d* was extracted from the model and presented below in Table 2.

Sample	A	B	C	D	E
D/d	1.75	1.53	1.21	1.18	1.16

Table 2. FIMT *D/d* Ratios

The results clearly show that Sample A sustained the greatest deformation, while Sample E sustained the least deformation.

Samples A, B & E were designed to investigate the benefit of incorporating a copper conductor in the cable design. When Sample A (no copper conductor) is compared to Sample B (0.4mm thick copper conductor) & Sample E (0.6mm thick copper conductor) the *D/d* ratio shown in Table 2 shows the importance the copper conductor layer design has on improving the cable crush performance.

Samples B, C & D, were designed to investigate the effect of increasing PE insulation thickness. The crush modelling has shown that as the PE insulation thickness increases, the cable structures sustained a gradual decrease in deformation as shown by the *D/d* ratio in Table 2.

In order to verify the finite element cable crush model results some physical cable experiments where undertaken. The experimental work completed is described below.

3. EXPERIMENTAL VERIFICATION WORK

The experimental verification of the finite element modelling of the cable crush performance involved the testing of three cable elements: Fiber metal tube (FIMT), Light weight optical cable (LW) and Double outer armoured optical cable (DA).

The test equipment used in the experiment are as follows:

Equipment	Number/Version	Manufacturer
FSM-80s optical fiber fusion splicer	FSM-80s	Fujikura
SLED stabilized light source	EBS400045-02	EXALOS
Four channels optical power meter	N7748A	Agilent Technologies
Tensile testing machine	WDW-50	Shanghai Hualong

Table 3. Experimental test equipment

The cable sample used was approximately 10 meters in length, with the optical fibers spliced into a loop. The head of the loop was connected to the optical power meter. In the experiment, the cable was crushed between plates over a length if 100mm and the compressive crush load held for 15minutes. During this time the optical fiber attenuation on the screen of optical power meter was monitored and if it increased rapidly the test was ended. The deformation of the cable sample under test was also monitored and after the test the cable was dissected to investigate the effects of the crush loading.

Figure 4. Experimental Test Set-Up

3.1 CRUSH RESISTANCE OF FIMT

The FIMT is one of the most important elements in submarine cable for protecting the optical fibers. When the FIMT is subjected to pressure or crush loads, the ability to resist deformation reflects in the communication performance of the optical fibers. The crush resistance of FIMT mainly depends on the wall thickness, outer diameter and the quality of the weld line of the metal tube.

3.1.1 INFLUENCE OF THE TUBE WALL THICKNESS AND OUTER DIAMETER

To evaluate the influence of the metal tube wall thickness and outer diameter, 4 different FIMT elements were tested under the same conditions. The FIMT test elements are shown in Figure 5 and results are presented in Table 4 and Graph 1.

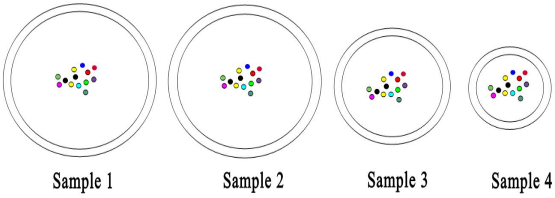
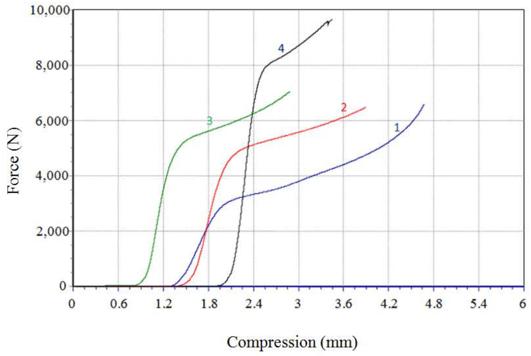


Figure 5. The structure of different FIMT

Structure	Value			
	1	2	3	4
Wall thickness, t（mm）	0.25	0.3	0.25	0.25
Outer Diameter, D（mm）	5.0	5.0	3.8	2.7
D/t	20	16.67	15.2	10.8
The force in the turning point (kN)	3.32	5.08	5.55	7.7

Table 4. The structure and crush resistance force of different FIMT elements



Graph 1. FIMT Force Compression curve

The experimental results appear to show that the deformation of the metal tube is initially elastic but when the force reached a critical point (the knee, or turning point in the curves above), the deformation rate increased rapidly and the FIMT deformation is plastic. Finally the test loop of fiber developed an optical loss when the force reached the maximum value and the test was stopped.

The data in Table 4 and the curve in Graph 1 reveal some interesting trends. When the results of Samples 1, 3 & 4, are examined it is seen that for samples having the same tube wall thickness as the diameter of the tube decreases the crush performance increases.

Comparing the results for Samples 1 and 2, (which have the same outer diameter), the crush resistance of the FIMT increased as the wall thickness of the FIMT increased.

The relationship between external pressure and tubes is shown in the following:

$$P=2\ T_b*[ó]_t/\ D_0 \ .... \ \text{(equation 1)}$$

where P-pressure; T_b-thickness; D_0-outer diameter; $[ó]_t$-allowable pressure of material.

The equation shows that the Pressure is in direct proportion to T_b/D_0 for the same material properties. So the crush resistance of the FIMT improves with a smaller outer diameter and a larger wall thickness.

3.1.2 THE INFLUENCE OF WELD LINE

To investigate the influence of the weld line on crush resistance the crush load was applied at different angular positions relative to the axial weld line and the results were show in Table 5.

Thickness of FIMT (mm)	FIMT O.D. (mm)		
0.25	3.8		
Welding location (degrees)	⬆ 0 degrees	➡ 90 degrees	↗ 45 degrees
The force in the turning point (kN)	5.75	5.77	5.82

Table 5. The Crush Resistance of FIMT relative to the Weld Line

The result presented in Table 5 show that the weld line position of the metal tube has negligible influence on FIMT's crush resistance. So we can consider that the quality and strength of weld line is as same as the tube itself.

3.1.3 THE ELASTIC LIMIT OF THE FIMT UNDER CRUSH LOADING

In Graph 1 it was observed that there was a knee, or turning point in the Force - Compression curve which appeared to indicate the transition between elastic and plastic deformation of the FIMT structure.

To confirm this point, the FIMT structure was compressed using force levels above and below the knee point in the curve.

As the knee, or turning point in the stress strain curve for the FIMT (0.25* Ø 3.8) occurs at 5.55kN, tests were completed under the condition of 4kN and 8kN respectively, see Table 6.

The structure of FIMT	0.25* Ø 3.8	
Crush force （kN）	4	8
The recovery situation after unloading pressure	Small deformation which recovers when the pressure is removed	Large deformation which does not recover when the pressure is removed

Table 6. The recovery situation after unloading different pressure

The tests indicate that the pressure force equivalent to the knee in the Force Compression curve has an extremely important significance in the FIMT crush performance. Below the knee, the deformation of FIMT is elastic deformation, and the deformation can recover when the pressure is removed. However above the knee, the FIMT suffers plastic deformation, which is permanent deformation, and in this condition, the FIMT crush performance is at risk.

We can conclude that the crush force at the knee of the Force Compression curve is the conservative limit of crush resistance for the FIMT cable element.

3.2 CRUSH RESISTANCE OF LW

The protective structure of LW cable involves protecting the FIMT element with inner armour wires, copper conductor and PE insulation. These additional cable elements improve the cable crush resistance. When the LW cable structure is subjected to a large lateral pressure, the FIMT inside will deform as shown in Figure 6.

We consider that if $D/d \leq 1.15$, the cable performance will not be affected even when subjected to 83MPa hydrostatic pressure. Therefore the crush force which produces a cable deformation where $D/d=1.15$ is termed the safe force.

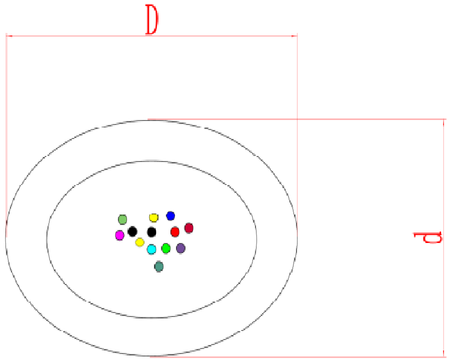


Figure 6. The deformed shape of FIMT under lateral pressure

3.2.1 THE INFLUENCE OF INNER ARMOURING LAY LENGTH

To investigate the influence of the inner armour lay length, cable samples were prepared where all other cable parameters were kept constant and only the inner armour lay length was varied. Crush tests were repeated with the crush load held for 15 minutes. The results are presented in Table 7.

The experimental results showed that: The crush resistance of LW cable has a tendency to improve as the lay length of inner armouring is decreased. With a shorter lay length the stronger the cable crush resistance.

While the use of a short lay length provides a good technical solution to improving the cable crush performance, in production the use of a short lay length results in slower cable throughput speeds.

To maintain cable throughput speeds other means of improving the cable crush performance should be investigated.

Structure of FIMT	0.25*Ø3.8			
Structure of inner armouring	Ø1.69*10		Ø1.69*10/ Ø1.69*16	
sample	a	b	c	d
Lay length (mm)	150	250	150	250
Thickness of PE insulation (mm)	1.5	1.5	1.5	1.5
Outer diameter (mm)	10.5	10.5	13.9	13.9
1.15 Safe force#（kN）	8	7	12	8
The force when fiber appear loss（kN）	13	12	13	12

Table 7. The structure and crush resistance of cable with different lay length

3.2.2 THE INFLUENCE OF COPPER CONDUCTOR AND PE INSULATION

To investigate the influence of the copper conductor and PE insulation, 5 cable samples were manufactured to reflect the cable structures modelled by the finite element analysis and reported in Figure 2. The 5 cables were subjected to crush tests and the parameters and result are presented in Table 8.

The cable samples were manufactured as follows : Sample A with no copper conductor, Samples B, C & D have the same copper conductor wall thickness and increasing PE wall thickness, Sample E was manufactured with a thicker copper conductor wall thickness.

When compared to the FIMT alone which has a safe force of 5.55kN, the addition of inner armour and PE insulation (Sample A) has improved the crush resistance by 134%.

The experimental results show that the cable crush resistance will be significantly increased with the use of a copper conductor applied around the inner armour. An improvement from 13 to 21 kN was observed (a 61% improvement) for Samples A & B, when a copper conductor was added.

Sample	A	B	C	D	E
The structure of FIMT	0.25*Ø3.8				
The structure of inner armouring	Ø1.69*10/Ø1.08*10+ Ø1.46*10				
Lay length（mm）	190				
The structure of copper conductor（mm）	None	0.4	0.4	0.4	0.6
The thickness of PE insulation（mm）	2.8	2.8	3.9	4.9	2.8
O.D（mm）	15.8	15.8	18	20	15.8
1.15 Safe force（kN）	13	21	23	24	24
The force when fiber appear loss（kN）	22	26	31	35	28

Table 8. The crush resistance of LW with different cable elements.

Sample B represents an improvement in crush resistance of the FIMT alone of over 270%.

A thicker copper conductor can also help to enhance the crush resistance as seen from the increase from 13 to 24 kN (an 84% improvement) for Samples A & E.

Sample E represents an improvement in crush resistance of the FIMT alone of over 330%

It can be concluded that the structure of copper conductor plays a key role in the process of crush resistance.

The copper conductor acts like a belt to assist in keeping the inner armour wires in position during the applied crush loading. By maintaining the inner armour wires in their design position clearly enhances and improves the cable crush performance adding protection for the FIMT element.

Similarly, as the copper conductor wall thickness increases the ability to maintain the inner armour wire position improves and so the cable crush resistance will be enhanced.

Comparing the experimental results of Samples B, C & D show that: When the other structures are the same, the crush resistance improves with the increase of PE sheath thickness.

Sample B represents an improvement in crush resistance of the FIMT alone of over 270%.

Sample C represents an improvement in crush resistance of the FIMT alone of over 310%.

Sample D represents an improvement in crush resistance of the FIMT alone of over 330%.

From the 1.15 safe force, the influence of PE sheath thickness on the crush resistance is relatively limited. It can be seen that for a 39% increase in PE thickness the crush resistance increases 9% (samples B and C), and for a 75% increase in PE wall thickness, the crush resistance increases by 14% (Sample B and D).

However, the influence of PE sheath thickness on the crush resistance is relatively important when investigating at the force required to initiate fiber loss. This is because as lateral pressure is increased, the PE sheath will deform first, increasing the contact area between the LW and clamp surface, thereby reducing the pressure applied to the LW cable and protecting the FIMT inside.

These practical experiments verify the finite element study results as the relative crush resistance ranking for cables with no copper conductor, 0.4mm thick copper conductor and 0.6mm thick copper conductor show the same performance trend in both the Finite Element simulation and the experimental work.

3.3 THE INFLUENCE OF OUTER ARMOURING

To investigate the influence of the outer armouring, two DA cable structures were manufactured with different wires sizes and numbers as shown in Table 9.

As one might expect the results indicated the outer armouring has a big influence on the crush resistance of the cable structure (when the cable cores have the same structure).

	F	G
The Structure of FIMT	0.25*Ø3.8	
The Structure of inner armouring	None	
The thickness of copper conductor（mm）	None	
The thickness of PE insulation（mm）	4.5	
The O.D of PE insulation（mm）	12.8	
Crush resistance of LW（kN）	13.0	
The structure of outer armouring（mm）	Ø4.2*12 + Ø5.0*16	Ø2.7*17 + Ø4.2*16
O.D（mm）	Ø39.2	Ø33.8
Crush resistance of DA 15min（kN）	＞50	40

Table 9. The crush resistance of different DA Cable Structures

Sample F represents an improvement in crush resistance of the FIMT alone (5.55kN) of over 800%. The outer armour has improved the crush resistance of the LW cable core (13.0 kN) by over 280%.

Sample G represents an improvement in crush resistance of the FIMT alone (5.55kN) of over 600%. The outer armour has improved the crush resistance of the LW cable core (13.0 kN) by over 200%.

The crush resistance of sample F is clearly greater than sample G. This is due the ability of the larger diameter armour wires to resist deformation and displacement. If the strength and the O.D of steel wire is selected to be larger, it can more effectively protect the inner cable core.

4. CONCLUSION

The crush resistance of the FIMT cable element, LW cable and DA cable have been analyzed by the finite element method and the results verified by practical experiments.

The following conclusions can be made:

1. A method has been developed where the crush performance of cables can be accurately modelled by a Finite Element Technique. This will allow a better understanding of the crush performance of new cable designs in the future, prior to manufacturing trials.

2. The FIMT cable element has a major contribution to the overall cable crush resistance. It has been shown how each additional cable manufacturing process increases and amplifies the crush performance of the cable structure. When designing cables for improved crush resistance, a FIMT with a low value of tube diameter/wall thickness ratio will maximise the cable crush resistance.

3. It has been demonstrated that the copper conductor element is very important in the process of improving cable crush resistance. When properly designed and manufactured, the copper conductor can provide a tight supporting grip on the inner armouring wires. The copper conductor assists the inner armour wires to maintain their design position and original structure during compression, hence improving the crush resistance.

4. The diameter/wall thickness ratio of the PE sheath has been shown to influence crush resistance. A small value of diameter/thickness is beneficial to improving crush resistance. The improvement in crush performance is less pronounced than that achieved by designing the FIMT and Copper conductor correctly.

5. The FIMT and copper conductor have been shown to be the most important elements which have the greatest impact on improving the crush resistance of LW cable.

6. At all stages of the cable manufacturing process, each protective layer must be applied with the highest quality standards.

7. It has been demonstrated that the selection of larger diameter outer armour wires is a key point in increasing the overall cable crush resistance.

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