International Journal of Impact Engineering 107 (2017) 58–79

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Spiral strand cables subjected to high velocity fragment impact

R. Judge[a,b,*], Z. Yang[c,d], S.W Jones[a], G. Beattie[b], I. Horsfall[e]

[a] Blast & Impact Research Centre, School of Engineering, the University of Liverpool, L69 3GH, UK
[b] Arup, Liverpool L3 9QJ, UK
[c] Centre for Low Impact Buildings, Faculty of Engineering and Computing, Coventry University, CV 5FB, UK
[d] College of Civil Engineering and Architecture, Zhejiang University, China
[e] Cranfield University, Shrivenham SN6 8LA, UK

ARTICLE INFO

Article History:
Received 6 October 2016
Revised 30 April 2017
Accepted 30 April 2017
Available online 1 May 2017

Keywords:
Spiral strand cable
Non-linear finite element method
Fragment simulating projectile
Impact
Modified Johnson–Cook model
Cockcroft-Latham
LS-DYNA

ABSTRACT

Structural cables are widely adopted around the world in offshore construction, sports stadia, large scale bridges, Ferris wheels and suspended canopy and fabric structures. However, the robustness of such structures to blast or impact is uncertain with a particular concern related to the loss of a primary structural cable when damaged by high velocity blast fragmentation. This paper presents the first ever numerical and experimental study on commonly used high-strength steel spiral strand cables subjected to high velocity fragment impact. Spiral strand cables were impacted by 20 mm fragment simulating projectiles travelling at velocities between 200 and 1400 m/s. Complex 3D non-linear finite element models were developed and carefully compared with experimental tests. The penetration resistance of the cables and resultant damage were studied with respect to fragment impact velocity. It was found that for all the impact velocities, the fragment penetration depth was less than half of the cable diameter demonstrating a considerable amount of resilience. Considering the damage caused, the residual cable breaking strengths were estimated and found to be still higher than the minimum breaking load of an un-damaged cable. The numerical models were also able to reproduce the main features of the impact tests, including the extent of localised damage area, the fragment penetration depth and mode of individual wire failures, thus demonstrating their potential to be widely used in industry for structural resilience and robustness assessments by structural engineers.

1. Introduction

Cable supported structural systems are widely adopted in offshore construction (e.g. deep water mooring systems), sports stadia roof structures, large scale bridges, Ferris wheels and suspended canopy and fabric structures. They offer economic and innovative structural solutions due to their strength-to-weight ratio when compared to other structural systems e.g. reinforced concrete and steel framing systems. A great deal of research and development has been carried out over the years to better understand the physical behaviour of such systems, most of which has found its way into design guidelines and international codes of practice for use by the practicing engineer. Most of this work has focused on cables subjected to quasi-static axial loading conditions [1]. More recently however, the robustness of such structures to highly transient loading conditions such as a blast or impact has come into focus. A particular concern associated with cable supported structures is that of sudden cable loss leading to disproportionate damage or collapse of part or all the structure [2,3,4]. Zoli and Steinhouse [5] assessed the vulnerability of the typical cable types used in cable-stayed and cable-suspended bridges, and highlighted that there are a number of potential mechanisms capable of inducing sudden cable loss, including the impact of explosively formed fragments travelling at high velocity as depicted in Fig. 1.

The work presented in this paper forms part of a larger research programme to investigate the overall robustness of cable supported structures in the event of sudden single or multiple cable loss and is largely supported by industry due to the lack of guidance available. The primary focus of this paper is to develop a better understanding of the levels of damage structural cables can sustain when subjected to high velocity fragment impact and whether or not such damage has the potential to induce sudden cable loss. This initial study is the first of its kind and thus this paper is a first step forward in understanding the robustness of such structures to highly transient loading conditions.

The approach taken to conduct the study was a combination of laboratory tests and numerical simulations. The geometric details and mechanical properties of the cables studied are outlined in Section 2. In the absence of real fragment data from an accidental or malicious explosion, the fragments used in the impact tests were standard 20 mm fragment simulating projectiles (FSP) [6].

---

[*] Corresponding author.
E-mail address: ryan.judge@liverpool.ac.uk (R. Judge).

http://dx.doi.org/10.1016/j.ijimpeng.2017.04.026
0734-743X/

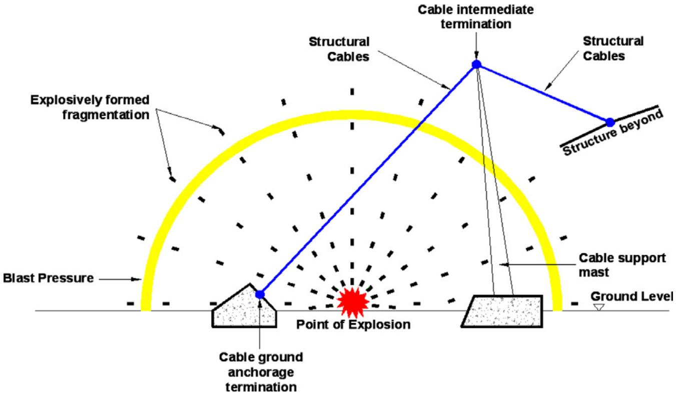

Fig. 1. Problem schematic.

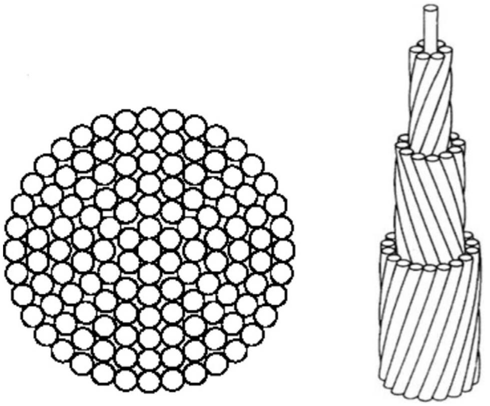

Fig. 2. A typical cross section and side elevation of a spiral strand cable [10].

Table 1
Typical mechanical properties of 1570 MPa and 1770 MPa wires.

Wire grade (MPa)	Wire diameter (mm)	Breaking load (kN)	0.2% Proof stress $\sigma_{0.2}$ (MPa)	Ultimate tensile strength (MPa)	Elongation %	Area reduction %
1570	5	34.11	1435	1737	8.79	23.26
1770	5	37.34	1623	1902	10.85	34.41

The testing conducted in this study was limited but nevertheless provided a good initial insight into the morphology and degree of damage that might be induced in a structural cable when subjected to fragment impact at velocities ranging from 200 to 1400 m/s. In practice, the cables would be subjected to an axial tension before and after impact. However, due to safety restrictions within the firing range related to the levels of pre-stress required to achieve a working tension load, the cables could not be pre-tensioned and further tests are planned to study the implications of this on the impact damage zone.

Alongside the testing, full 3D non-linear finite element (FE) models of the cables were developed in LS-DYNA [7], with careful considerations given to the complex geometry of the cables, inter-wire contact mechanics, cable-end boundary conditions and appropriate material modelling. The numerical and experimental results were carefully compared, with particular attention paid to the localised damage area, the fragment penetration depth, the number of heavily indented and totally fractured wires, resulting in an estimation of the residual cable breaking load post impact.

This paper is organised as follows: In Section 2, the spiral strand cable physical and mechanical properties are presented along with an estimative equation later used to predict residual cable breaking loads. In Section 3, the experimental test set-up is highlighted and the results of the impact tests are presented. This includes a qualitative metallurgical study of the wire fracture and damage mechanics using scanning electron microscopy (SEM) and an evaluation of cable damage. In Section 4, the formulation of finite element models of the cable impact tests is presented outlining the boundary conditions, element formulation, contact mechanics and constitutive relations used to represent the material behaviour on impact. Section 5 compares the results of the experimental testing and numerical simulations and highlights areas where further research and development is required. Section 6 concludes the findings of the study.

2. Spiral strand cables

Spiral strand cables are commonly used as backstay and main support cables in the structural systems described at the start of Section 1. They comprise many groups of individual high strength round steel wires. The wires are manufactured from high carbon steel with nominal tensile strengths in the range of 1570 MPa–1960 MPa [8,9]. The wires are hot-dip galvanized for corrosion resistance before they are assembled into a structural cable. The cables are built-up using circumferential layering in which the wires in each layer are spirally wound around a central wire and spun in opposite directions. This minimises both residual torque and wire de-coiling as a result of the elastic stress induced in the wires during the winding process. A typical spiral strand cable is shown in Fig. 2 [10].

Uniaxial tensile strength tests on individual wires are normally carried out by the cable manufacturer to obtain an engineering stress-strain relation which is used to determine the basic mechanical properties. A measure of wire ductility is also established from the wire elongation and reduction in cross-sectional area at failure. Typical test data provided by the cable manufacturer, Bridon International Ltd, for both 1570 MPa and 1770 MPa UTS wires of 5 mm diameter are listed in Table 1, where 0.2% proof stresses are given because it's often difficult to pinpoint the exact stress at which plastic deformation occurs on the stress-strain curve.

The cable chosen for investigation in this study is a 60 mm diameter spiral strand which consists of 120-wires with a nominal UTS of 1770 MPa. It has one straight central core wire and six outer layers of wires, with each layer spirally wound in opposite directions over one another around the central wire. The spiral angle, known as the lay angle, is related to the lay length of the individual wires. The lay length describes the distance after which a wire reappears at the same angular position along the longitudinal axis of the cable. It is different for each layer of wires as the diameter of each layer increases. The breaking strength of the cable is dependent on the lay length, being smaller for shorter lay lengths and greater for longer lay lengths. The geometric details of the cable are listed in Table 2.

The common value for most design standards e.g. [11,12] is the minimum breaking load (MBL) which is the load that will always be achieved in a breaking load test. The MBL is also referred to in some design standards as the characteristic breaking load or the nominal cable strength and it is a value that is quoted by cable manufacturers in technical literature. The minimum breaking load is derived using partial safety factor philosophy which is also referred to as the Load Resistance Factor Design. The design resistance $Z_{R,d}$ of a cable