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Cross section shape optimization of wire strands subjected to purely tensile loads using a reduced helical model

Francesco Maria Filotto^{1*} , Falk Runkel² and Gerald Kress³

*Correspondence:

ffilotto@ethz.ch

¹Experimental Continuum
Mechanics Group, IMES, ETH
Zürich, Leonhardstrasse 21, 8092
Zürich, Switzerland

Full list of author information is
available at the end of the article

Abstract

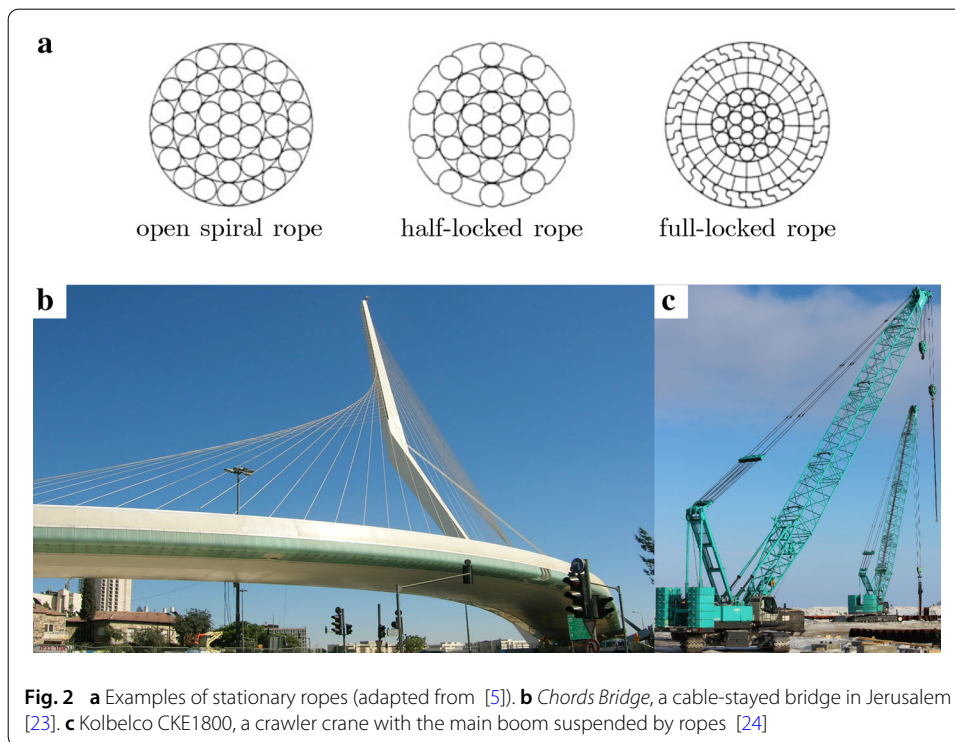
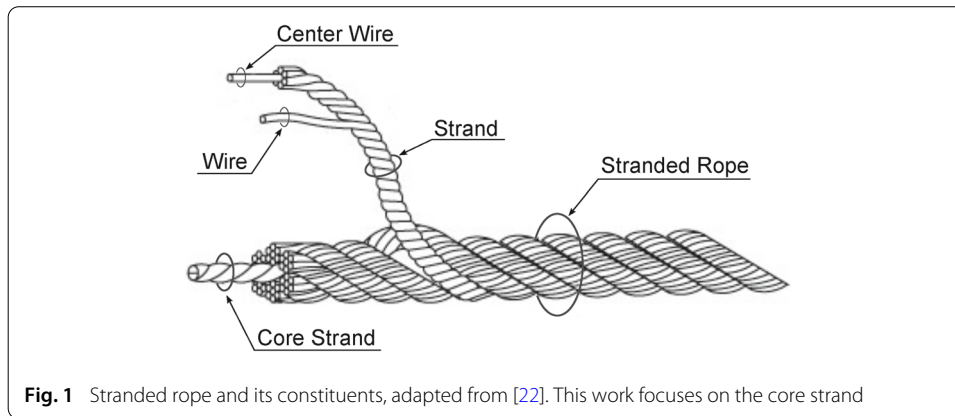
This paper introduces a shape optimization of wire strands subjected to tensile loads. The structural analysis relies on a recently developed reduced helical finite element model characterized by an extreme computational efficacy while accounting for complex geometries of the wires. The model is extended to consider interactions between components and its applicability is demonstrated by comparison with analytical and finite element models. The reduced model is exploited in a design optimization identifying the optimal shape of a 1 + 6 strand by means of a genetic algorithm. A novel geometrical parametrization is applied and different objectives, such as stress concentration and area minimization, and constraints, corresponding to operational limitations and requirements, are analyzed. The optimal shape is finally identified and its performance improvements are compared and discussed against the reference strand. Operational benefits include lower stress concentration and higher load at plastification initiation.

Keywords: Wire strand, Reduced model, Helical structures, Shape optimization, Genetic algorithms

Introduction

Wire ropes are basic structural elements in engineering and construction. Thanks to their complex hierarchical composition, wire ropes design permits to achieve a response tailored for specific applications and load cases. They are used as a structural link in bridges and cranes, for lifting objects or as tracks in cable-ways. They offer high longitudinal stiffness, while keeping a low transversal bending stiffness. This allows for easy storage, movement and deployment, thanks to the use of drums, sheaves and pulleys [1].

Even though many different designs have been proposed throughout history [2,3], the general composition of a *rope* (see Fig. 1) has not changed. The basic element is the *helical wire*, arranged in a bundle to form a *strand*. The obtained strands can be themselves helically arranged to obtain the *stranded rope*. Compared to fibre materials used in *fibre ropes* (that have been in use for millennia [2]), the use of structural materials allow for an increased load carrying capability.



The mining field in the 19th century was a driving industry for the development of wire ropes: the aim was to replace the employed metal chain—characterized by small damage tolerance—with an element that would be comparable in structural response. This is achieved by using rope designs, where multiple load paths architecture provides time for servicing and replacing the damaged component, avoiding catastrophic failure [4].

Out of the vast number of rope applications, this work focuses on those where loads are mainly tensile, in which case stationary ropes are employed [5]. They are utilized, for example, in cable-stayed bridge, in cable-ways and in cranes as guy lines for booms suspension (see Fig. 2). They can also be found in civil constructions in the form of pre-stressed concrete strands [6]. Stationary ropes are usually multi-layered strands, having therefore each component in a single helical configuration, as opposed to stranded ropes described above.

Ropes have many geometrical parameters in defining the overall response of the strand [5]. While at the level of the strand and the rope there are numerous combinations of parameters (number of wires, layout, lay-factor), the very basic component, the wire, offers most often only its diameter as degree of freedom, due to the ease and lower costs in manufacturing circular wires. As a consequence, strands present local stress concentrations due to the radial pressure concentration at the wires contact locations. Departing from the geometrical constraint of round wires, the aforementioned design drawbacks are mitigated permitting to achieve optimized overall operational characteristics.

For the case of tensile-dominated applications where single strands are used, the focus will be on providing examples of how the geometry could be optimized for minimum weight or minimum stress concentration, while satisfying application-dependent requirements such as limit load, axial stiffness, axial load at plastification or bending stiffness. $1 + 6$ strands are basic, yet among the most used, strands. It has been chosen as reference strand in this work for its relatively straightforward geometry. Accordingly, a novel geometrical parametrization for the $1 + 6$ wire strands is proposed.

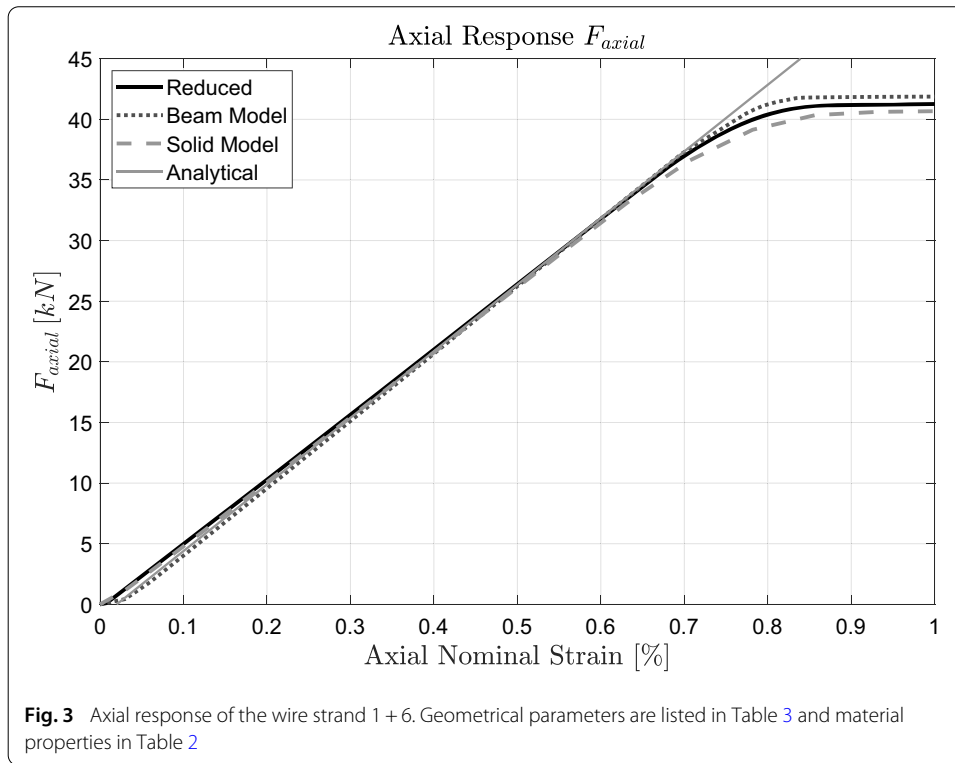
For the analysis to come, a reduced model [7] is employed. Rope theory literature has been developed since the 1860s and a plethora of models have been proposed. Complexity of analytical models for wire strands span from the simple assumption of helical springs in parallel to a more refined curved beam theory, mainly based on Love's theory [8] or on general theory of rods by Green and Laws [9], accounting for bending and torsion. Besides, finite element (FE) models have also been employed to model more complex phenomena as residual stress after manufacturing [10], contact and friction [11] and electromagnetic interactions within power cables [12]. Reduced helical models [7, 13–15] have been introduced in more recent years and utilize the concept of helical symmetry to reduce the computational domain, have also been successfully used in various fields. The computational efficiency of reduced models and their ability to model complex geometries permit to challenge the limitation of purely circular wires and to propose an alternative approach to the strand design, by means of a shape optimization. In order to permit such a procedure, part of the considered domain needs to be modified to allow for the contact definition.

This paper is structured as follows: “Modeling techniques comparison” presents the modeling technique used and how it stands against alternative techniques; in “Optimization procedure” section the optimization framework is introduced and the selection of objectives and constraints is discussed; “Results” section contains the discussion on the performance benefits of the optimal shape compared to the reference and a sensitivity analysis carried on the resulting strand; finally, conclusions are drawn in “Conclusions” section.

Modeling techniques comparison

Reduced helical model

When a helical structure is deformed uniformly along its entire length, the state variables (strains and stresses) are uniform along helical lines. Its overall response can be exactly analysed by taking a representative two-dimensional surface. This is a property called *translational invariance* [14], and it is exploited to derive a reduced finite element model [7] whose formulation is similar in idea to the generalized plane strain elements [16].



Other models have been proposed that use this same property, such as those by Zubov [17], Treysede [13], Frikha et al. [14] and Karathanasopoulos and Kress [15]. Differently from the aforementioned models, the one used in this work has been derived within the finite strain framework, therefore being able to better describe the wire motions. Additionally, it was developed for complex geometries and interactions on the transverse cross section.

The reduced model permits to have a complex geometry, while keeping a low number of elements. This allows fine meshes and local strains and stresses to be studied, without the need of a volumetric FE and very computationally expensive simulations. On the other hand though, it is limited by its derivation assumption: only uniform loadcases can be studied, such as axial elongation and twist, radial compaction and thermal expansion [15]. Accordingly, any load case—which determines that each transverse cross section of the structure behaves identically—can be considered.

Requirements on modeling approaches

For our optimization, four requirements are essential to be satisfied by the chosen modeling technique. An analytical model as found in Feyrer [5], and two three-dimensional FE models (based on either on solid volumetric or beam elements) are compared to the reduced model.

Axial response As the axial elongation is the load case to optimize for, our model needs to be able to fully capture the interaction between wires, including stiffening due to contact among wires and material plasticity. Figure 3 shows how all models are able to predict the overall axial behaviour.

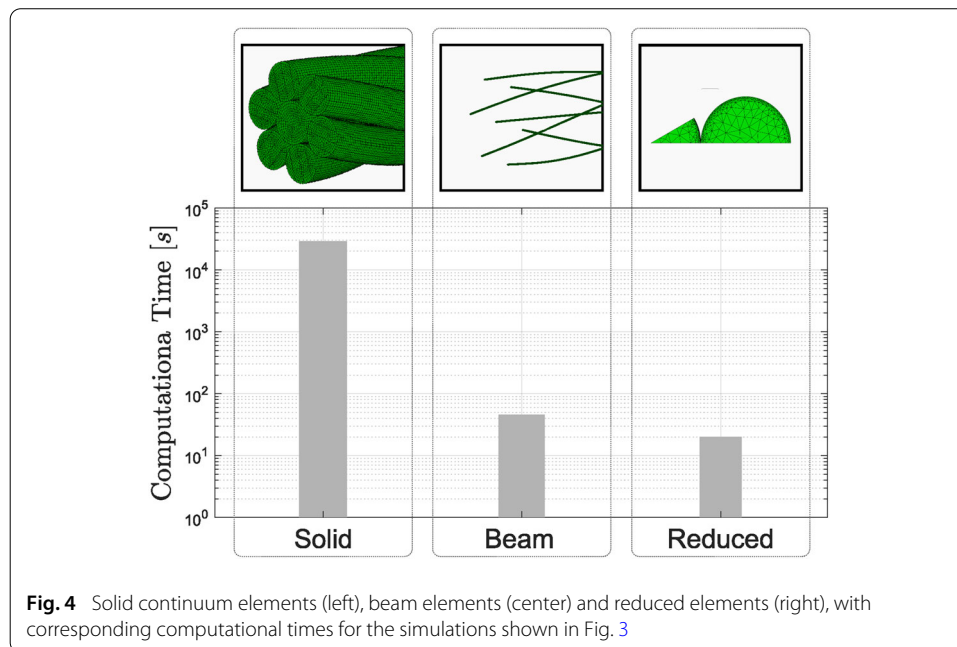


Table 1 Requirements met by each model

	Analytical	Solid	Beam	Reduced
Axial response	✓	✓	✓	✓
Computational efficiency	✓	✗	✓	✓
Complex geometry	✗	✓	✗	✓
Bending response	✓	✓	✓	✗*

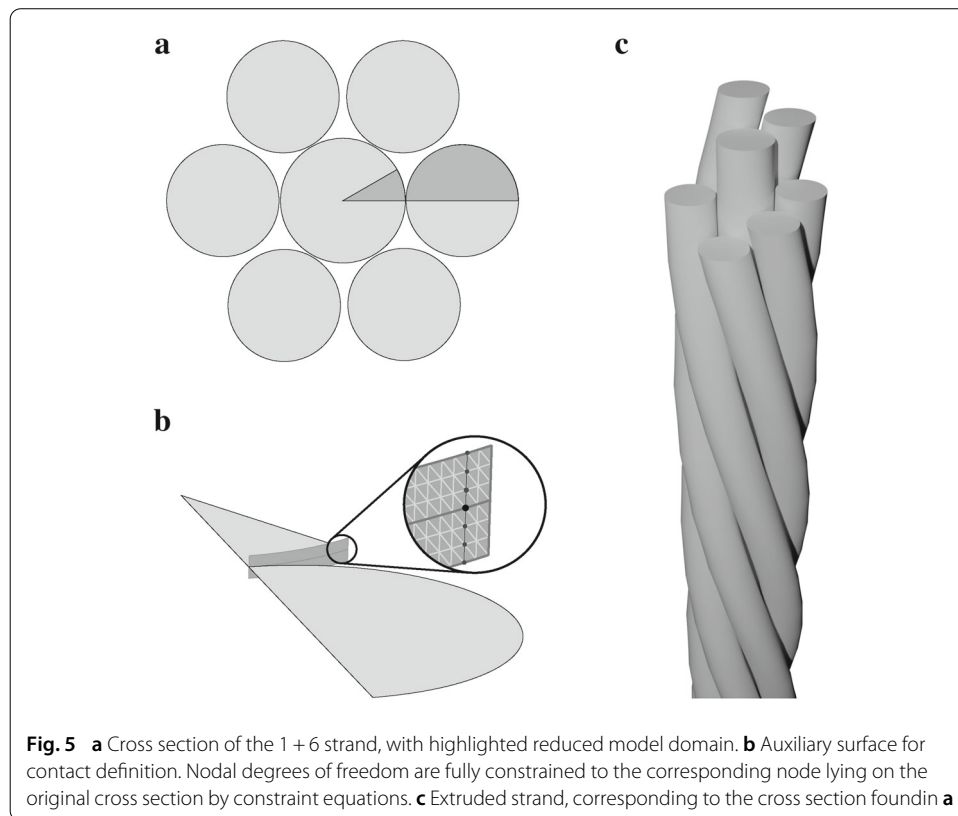
None of them is capable to fulfil all the requirements. * Bending stiffness approximated analytically ("Approximation of the bending stiffness section")

Computational efficiency A main focus when approaching an optimization routine is to assure that the core simulation—that computes the objective value—is as efficient as possible, as it is run multiple times. Therefore, in Fig. 4 a comparison between solution times to quantify the speed of each model is shown. Apart from the analytical model, the beam and reduced models are comparable in solving the analysis, with the solid FE being significantly slower.

Complex geometries With the goal of setting up a shape optimization, the chosen model will need to be able to fully describe the geometry of the strand (and in particular of the outer wire). Solid and reduced FE models are the only ones that satisfy this requirement, because both the analytical and the beam FE models rely on a narrow database of cross sections for contact definition.

Bending response A calculation of the bending response is also required in the optimization routine, to constrain the strand flexibility. Solid and beam FE models and analytical models can directly describe such a load case. The reduced model, on the other hand, because the transversal slices would not behave independently from their axial location, is inherently not capable of modeling bending.

Table 1 highlights how the reduced model stands out against the alternative modeling approaches.



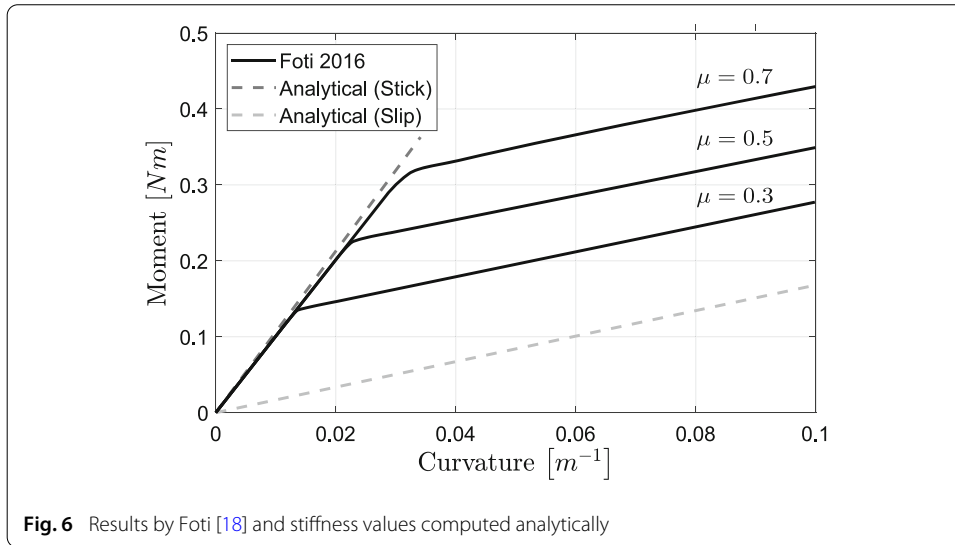
Extension of the reduced helical model to account for contact

Because the influence of contact between wires is important to fully characterize the stress state within the strand, an extension of the model found in [7] was required (Fig. 5b). The model was originally developed for the analysis of a single constituent, either free helices or solid regions (e.g. solid cylinder with inclusions). Strands have instead distinct components that are free to rotate and move relative to each other. Therefore, an interaction law needs to be introduced. Instead of simply merging the contact points [15], the current work uses a contact law with exponential pressure-overclosure behaviour.

In order to use the contact definitions already available in Abaqus, a geometrical expedient is introduced. Since each component is locally planar and there is a relative out-of-plane rotation, in order to enable a three-dimensional contact, an *auxiliary* master surface must be defined. This allows the interaction to actually represent a surface-to-surface contact rather than a line-to-line one, that would eventually create an artificial—localized—kink. This surface is obtained by extruding the nodes of the inner core perpendicularly to the reference plane. These nodes are then connected by shell elements and rigidly constrained to the corresponding parent nodes to guarantee the helical symmetry. Figure 5b shows such contact surface, with highlighted the nodes connected to the corresponding master node lying on the reference cross section.

Approximation of the bending stiffness

As suggested in the work by Foti [18], the bending of a strand exhibits two distinctive extremes.



- *Stick phase*, where the bending curvature is low enough that the friction between components prevents them from sliding relatively to each other. All wires form a cross section with connected elements associated with high bending stiffness.
- *Slip phase*, curvatures are high enough that friction can be ignored and each component is assumed to freely bend about its neutral plane, determining an overall reduction in bending stiffness.

The two values of stiffnesses, both in stick and in slip phase, are well approximated by the bending stiffness of the straight rod having the same transverse cross section.

$$K_{stick} = E_0 I_0 + \sum_{i=1}^6 E_i \tilde{I}_i \quad (1)$$

$$K_{slip} = E_0 I_0 + \sum_{i=1}^6 E_i I_i \quad (2)$$

where E is the Young modulus, I is the moment of inertia of the each wire with respect to its own neutral plane and \tilde{I} is the moment of inertia with respect to the strand neutral plane. Subscript 0 refers to the core wire, while values of $i > 0$ refer to the outer wires ($i = 1 \dots 6$).

This approximation allows us to consider bending without involving more complex models. Figure 6 shows how the analytically computed stiffness values match the results obtained by Foti [18]. However, the ability to characterize the transition between the two phases (that depends on the friction coefficient μ) is not maintained.

The axial force applied to the strand also influences the bending response [18], due to the increased friction at the contact between wires when the strand is elongated. Considering the fact that, for the applications considered in this work, axial forces are high and curvatures are low, the stick phase stiffness K_{stick} will be considered.

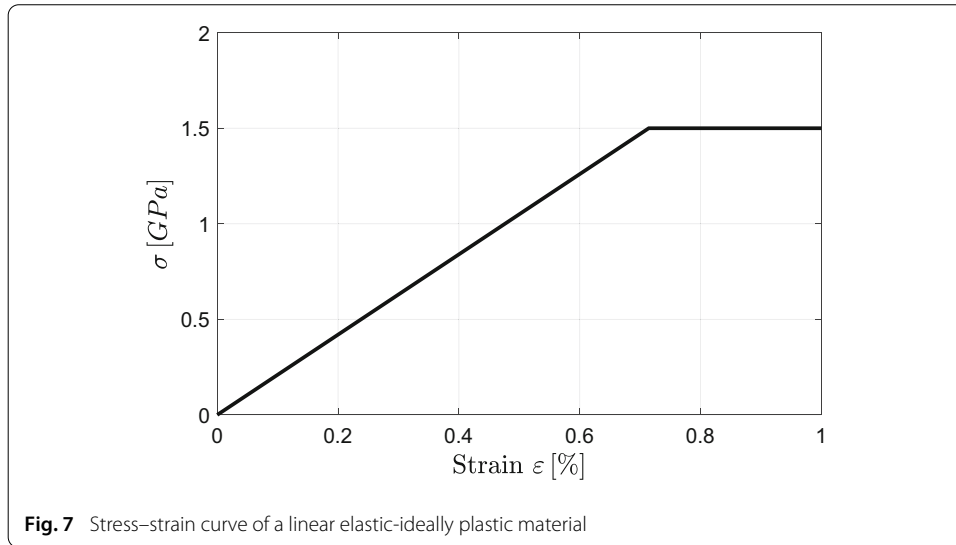


Table 2 Material properties used for both the reference for limit load analysis ($H = 0.0$ GPa)

Young modulus	E	210 GPa
Poisson's ratio	ν	0.3
Yield stress	σ_0	1.5 GPa
Hardness	H	0.0 GPa

Parameters remain constant throughout the optimization

Material model

Throughout all simulations presented here the material model is an elastic-ideally plastic constitutive law. Figure 7 shows the stress-strain curve corresponding to the material parameters as in Table 2. This choice of constitutive law allows to model failure by a *limit load analysis*. The material of the analysed structure is replaced by an ideally plastic material with lower yield stress. This makes the limit load, i.e. the maximum load the structure can sustain before plastic collapse, representative of the *breaking load*.

Optimization procedure

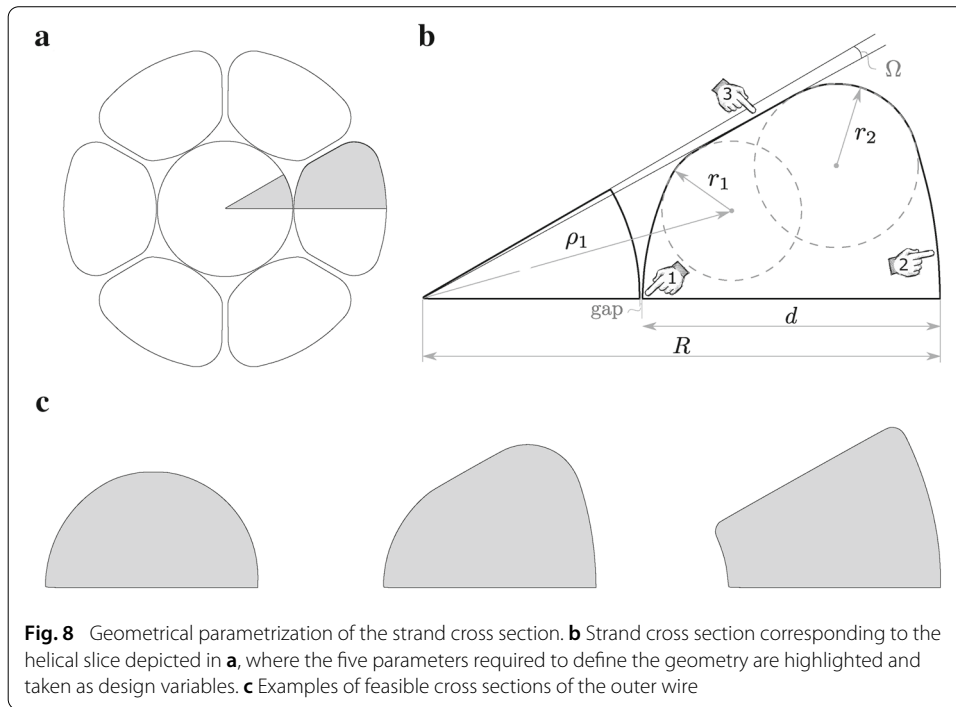
Objectives

The aim is to obtain wire shapes which reduce local stress concentration and therefore reduce plastification, fatigue damages, thereby extending life time. In addition, lightweight design increases structural efficiency and decreases material costs. As a result, it has been chosen to consider two objectives.

The first is *stress concentration* minimization, defined as

$$\gamma = \max \left(\frac{\sigma_{VM}^{max}}{\sigma_{VM}^n} \right) \quad (3)$$

where σ_{VM}^{max} is the largest Von Mises stress acting in the cross section (located at the *wire-to-wire* contact point) and σ_{VM}^n is the nominal value at the center of the core wire, i.e. the tensile stress occurring as a result of the applied deformation. Because of the nonlinear local response, the stress concentration at contact point varies with the applied load history. In particular, it will reach its maximum value γ at the initiation of plastification (Fig. 10).



The second objective is area minimization, that, at constant lay-length, directly translates into weight reduction. It is considered as the effective area covered by the material in the transverse cross section. Due to the choice of the ideally plastic constitutive law, when a limit load is given, the minimum value of the area is bounded by the yield stress.

Constraints

Optimization procedures need to have constraints that avoid infeasible solutions to be accepted. For instance, simplifying a rope structure to a single isotropic rod would prevent any stress concentration, therefore minimizing the objective. In such a case though, the rope would lose the favourable bending flexibility and damage tolerance, thereby not fulfilling fundamental requirements of rope structures. Such characteristics are main factors in the selection of ropes in an application and need to be maintained. While the damage tolerance is kept by solely considering a shape optimization (that keeps the multi-component nature of the strand, contrarily to a topology optimization), the bending stiffness is taken as inequality constraint, where the upper bound is defined by the bending stiffness K_{stick} of the reference strand.

Additionally, each application sets a maximum load the rope is required to carry. The *breaking load* of the selected rope needs to be higher than such value. Therefore, because the optimal shape needs to satisfy the same requirements as its respective initial geometry, the breaking load is considered as a constraint as well.

Geometrical setup

Figure 8 shows the geometrical parametrization used in the considered procedure. The optimization aims at a wide variability, while keeping the number of design parameters reasonably low. It presents a straight core wire and 6 helical wires around it. The analysis

considers constant the number of wires and the lay-length (i.e. the axial length corresponding to a full turn of an outer wire).

Figure 8b shows the degrees of freedom that our shape parametrization has. Besides the total strand wire radius R and the outer wire diameter d , the shape is parametrized by the use of two auxiliary circles that can be moved and scaled on the cross section. These fillets bring in a total of 3 parameters (ρ_1 , r_1 and r_2).

To fully define the geometry, the following geometrical constraints are imposed as well:

- Minimum interwire distance (*gap*) is set to be at the mirror plane (highlighted point 1 in Fig. 8b), to allow for the contact initiation;
- Concave outer shape, with a curvature corresponding to the radius of the strand, R (point 2);
- Flat outer wire surface (point 3) with given angular distance Ω , that permits relative movement between adjacent outer wires without contact.

In the case which reducing the concentration at the contact point is our objective, the optimal shape would morph into a shape that allows a surface-to-surface contact. Doing so would provide a larger area for radial force transmission and thus reduce the localization. We though encode the geometry so to have the contact surface to be concave or convex, in order not to restrict the design space. Figure 8c shows potential candidates satisfying the geometrical constraints.

Optimization routine

Because of the complex geometry and the geometrical constraints to be considered, a genetic algorithm has been chosen to find a global minimum of the considered problem. A pool of 100 different feasible geometries —based on the parametrization—has been created as initial population. The optimization is allowed to have up to 100 generations, with Matlab default values for mutation and crossover [19].

Each optimization has either area minimization or stress concentration minimization as single objective, as discussed in Section 3.1.

Constraints are enforced by a multiplicative penalty factor [20] as follows:

$$\tilde{f} = f \prod_{i=1}^n \left(1 + \frac{|g_i - \hat{g}_i|}{\hat{g}_i} \right) \prod_{j=1}^m \left(1 + \frac{\max(0, h_j - \hat{h}_j)}{\hat{h}_j} \right)$$

where g_i and h_j are the current values of the n equality constraint functions and m disequality constraint functions. \hat{g}_i and \hat{h}_j are the given constraint values and \tilde{f} is the objective value of the constrained problem.

Results

The reference strand taken as initial design is characterized by a 1 + 6 layout, with a core diameter of 2.50 mm and an outer wire diameter of 2.25 mm. Additional constant geometry properties, as the number of wires n , lay-factor LL , gap g and angular distance Ω are listed in Table 3. Material properties used correspond to an ideally plastic law, as discussed in “Material Model” section. The strand is extended axially to a nominal axial strain of 1%. The objective is stress concentration minimization and the selected constraints are the limit load and bending flexibility of the reference strand.

Table 3 Constant geometrical parameters of the reference strand

Number of wires	n	6
Lay-factor	LF	8.2
Angular distance	Ω	0.9°
Gap	g	0.0025 mm

Parameters remain constant throughout the optimization

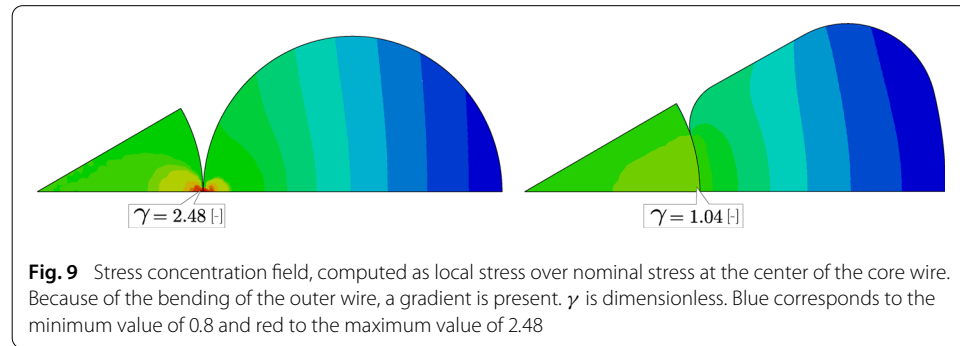


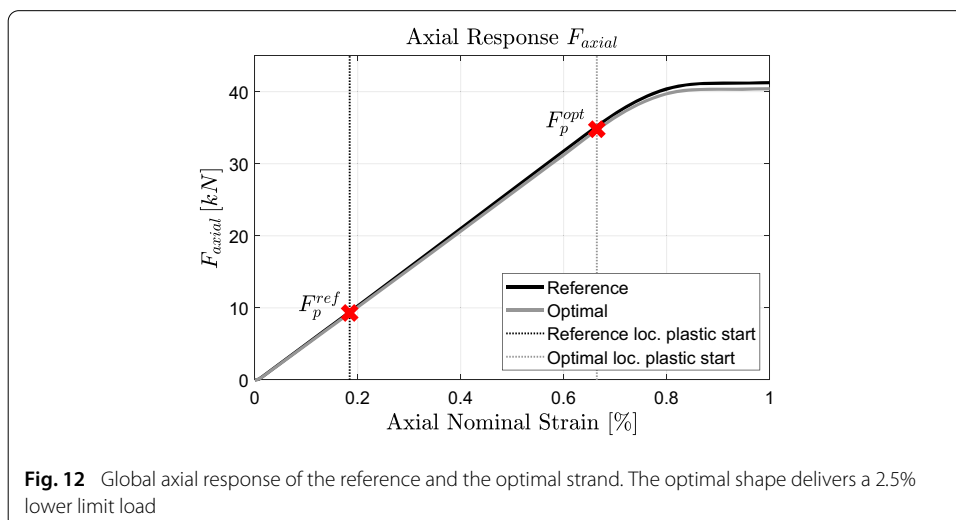
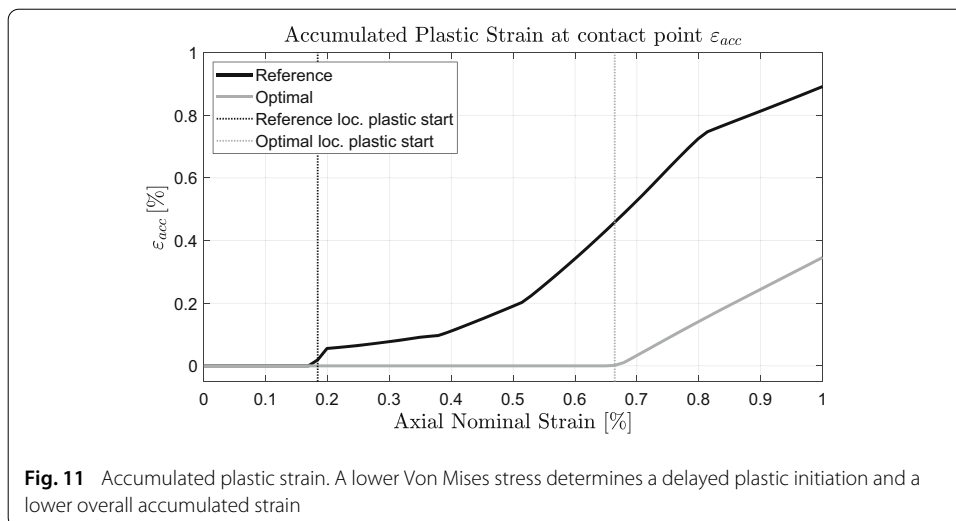
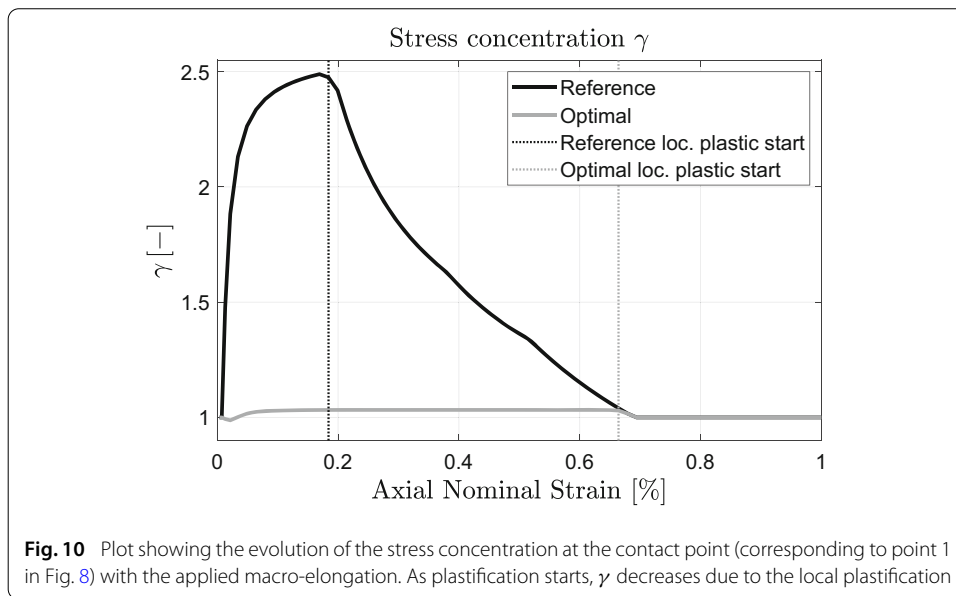
Fig. 9 Stress concentration field, computed as local stress over nominal stress at the center of the core wire. Because of the bending of the outer wire, a gradient is present. γ is dimensionless. Blue corresponds to the minimum value of 0.8 and red to the maximum value of 2.48

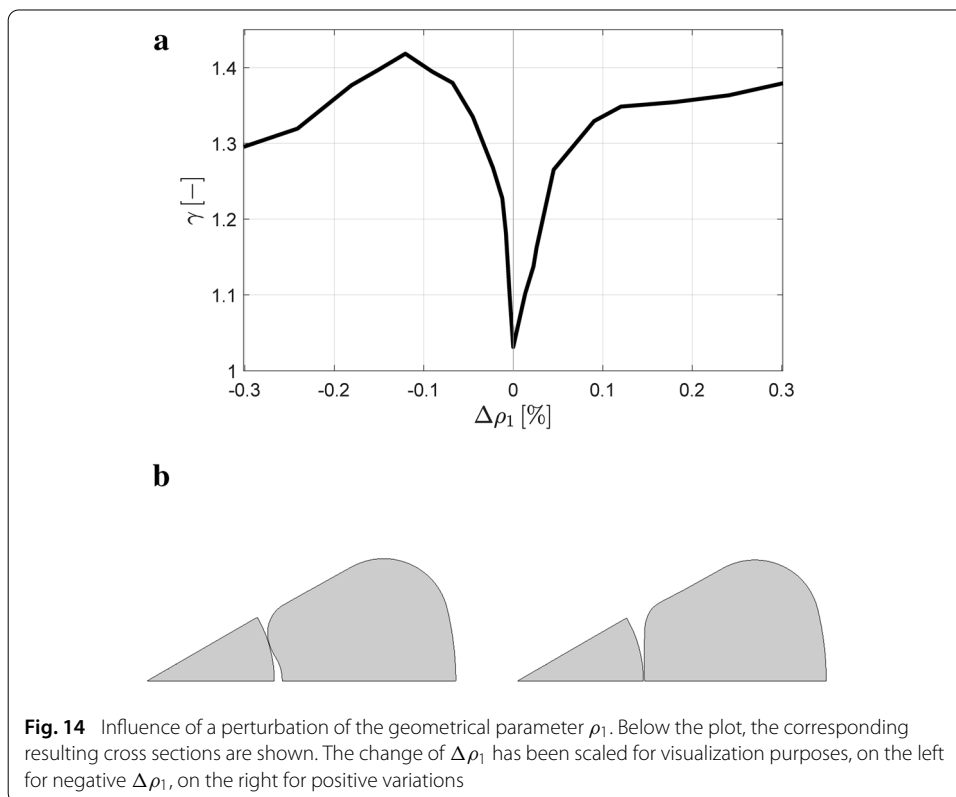
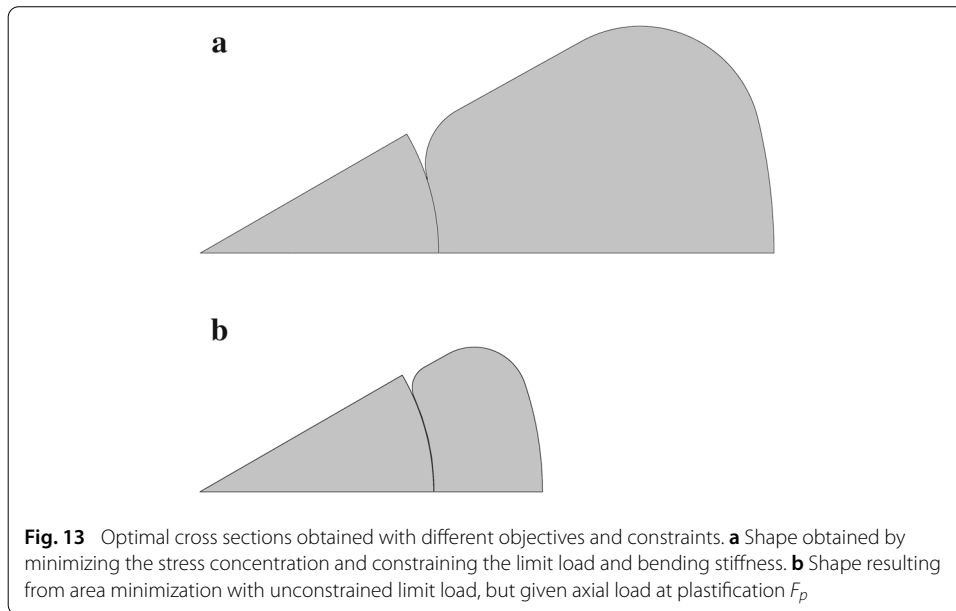
The optimization procedure is coordinated by the built-in Matlab R2018a *Optimization Toolbox* [19], while each simulation is solved by Abaqus 6.14 [21] with a custom subroutine (called *User Element*) developed in a previous work [7].

The optimal shape is shown in Fig. 9 on the right, where the contour of the Von Mises stress concentration, i.e. the stress normalized with the nominal value measured at the center of the core wire, is displayed. The increment plotted refers to the nominal strain at which the plastification starts, that corresponds (as shown in Fig. 10) to the highest stress concentration within the loading history. The pressure distribution associated with the *surface-to-surface* contact results in the reduction of stress concentration into a more homogeneous field in the new geometry. The reference strand has a maximum local Von Mises stress of 148% higher than the nominal stress (corresponding to a concentration $\gamma = 2.48$), while the optimal presents only a 4% higher Von Mises stress ($\gamma = 1.04$). The initiation of plastification happens therefore at significantly larger strains, as shown in Fig. 11, where the accumulated equivalent plastic strain at the location of plastic initiation is plotted against the loading history. Delayed plastification means as well that the axial load that the structure can bear without having any local defects is increased, as it is highlighted in Fig. 12 by the value F_p^{opt} (34.8 kN) being 3.74 times higher than F_p^{ref} (9.3 kN).

Contrarily to Fig. 11, the curves in Fig. 12 do not show any effect of the early local plastification. This is due to the considerably small area affected by this phenomenon, making its contribution to the axial force is negligible. Figure 12 shows the force-strain curves and it can be seen that the limit load is kept as required by the constraint, with the optimal strand being more compliant than the reference strand by less than 2.5%. As for the bending flexibility, it showed the same value as the reference, with less than 0.1% variation.

Figure 13 presents another optimal shape, obtained with an alternative choice of objectives and constraints. When axial force at plastic initiation F_p is considered as the only constraint, the required transverse surface is allowed to decrease, because it is not bounded by the limit load requirement. If area minimization is therefore considered, the resulting shape shown in Fig. 13b is obtained, with the area value of 10.8 mm^2 , corresponding to





the 37% of the reference strand area ($A = 28.9 \text{ mm}^2$). A delayed plastification' start can provide margin for reducing the safety factor and consequently the required weight.

Sensitivity analysis

Any production process is subjected to tolerances, and thus it could be expected that the manufactured optimal wire would not match perfectly the computed one. To study this

sensitivity, it has been chosen to slightly vary a parameter ρ_1 , that determines the inner surface curvature of the outer wire. Figure 14 shows the maximum stress concentration measured when adding a small perturbation $\Delta\rho_1$ to the optimal $\hat{\rho}_1$. In both directions (whose corresponding geometries are illustrated in Fig. 14) there is a detrimental effect, due to the reintroduction of local concentration, losing partially the benefit of the optimal shape. Values are though significantly lower than the reference strand value ($\gamma = 2.48$). In particular, the results show that a larger ρ_1 ($\Delta\rho_1 > 0$, corresponding to a smaller curvature of the inner contact surface) is safer, as γ increases less for such values.

Conclusions

The reduced helical model capability to resolve local stresses has been proven essential to allow for the proposed optimization. It computes stress concentrations without recurring to a solid FE model, that would have rendered the entire routine computationally very expensive. Within the limitations set by the reduced helical model assumptions, the applicability and potential of the chosen approach was demonstrated by showing that a optimized design of the strand, and in particular of the outer wires, was found.

Such optimization framework complements the state-of-the-art design of strands, since an optimal cross section—providing beneficial characteristics—could be tailored to each application. The strand manufacturer would need to have ways to produce the resulting geometry by successive drawing through custom made dies. While this surely increases the complexity and cost of the strand manufacturing processes, it is feasible, as non-circular wires have already been used in full-locked spiral rope [5]. Compared to the *compaction* of strands—the process of radially compressing a strand that originally had round wires—the approach proposed in this work reduce dirt infiltration and determines a better contact pressure distribution, without introducing unwanted pre-stresses. This analysis can directly be extended to more complex geometries such as multi-layer strands and it could also be coupled with other models to analyse the next hierarchical level, the wire rope. For instance, the reduced model could compute the homogenized properties of the wire strand to be used in a beam model, that would effectively simulate a stranded wire rope.

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Authors' contributions

FMF performed the optimization simulations and analyses and wrote the paper. FR created the beam and solid models used in the present work and reviewed the paper. GK commented and reviewed the paper. All authors read and approved the final manuscript.

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Availability of data and materials

Data available on request from the authors. Plot data is found in the additional material "Plot_data.xlsx".

Competing interests

The authors declare that they have no competing interests.

Author details

¹Experimental Continuum Mechanics Group, IMES, ETH Zürich, Leonhardstrasse 21, 8092 Zurich, Switzerland, ²Inspire AG, Innovative Composite Structures, Technoparkstrasse 1, 8005 Zurich, Switzerland, ³Laboratory of Composite Materials and Adaptive Structures, Department of Mechanical and Process Engineering, ETH Zurich, Tannenstrasse 3, 8092 Zurich, Switzerland.

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