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To cite this article: Luca Arleo *et al* 2021 *Eng. Res. Express* **3** 035033

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Engineering Research Express

PAPER

Design methodology for the development of variable stiffness devices based on layer jamming transition

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Supplementary material for this article is available online

Abstract

Variable stiffness mechanisms as Jamming Transition draw huge attention recently in Soft Robotics. This paper proposes a comprehensive design methodology for developing variable stiffness devices based on layer jamming. Starting from pre-existing modelling, we highlight the design parameters that should be considered, extracting them from literature and our direct experience with the phenomenon. Then we validated the methodology applying the design process to previous layer jamming cases presented in literature. The comparison between the results obtained from our methodology and those presented in the analyzed previous works highlights a good predictive capability, demonstrating that this methodology can be used as a valid tool to design variable stiffness devices based on layer jamming transition. Finally, in order to provide the scientific community with an easily usable tool to design variable stiffness structures based on layer jamming transition, we have elaborated a Matlab script that guides the user through the main design parameters implementing the proposed methodology in an interactive process.
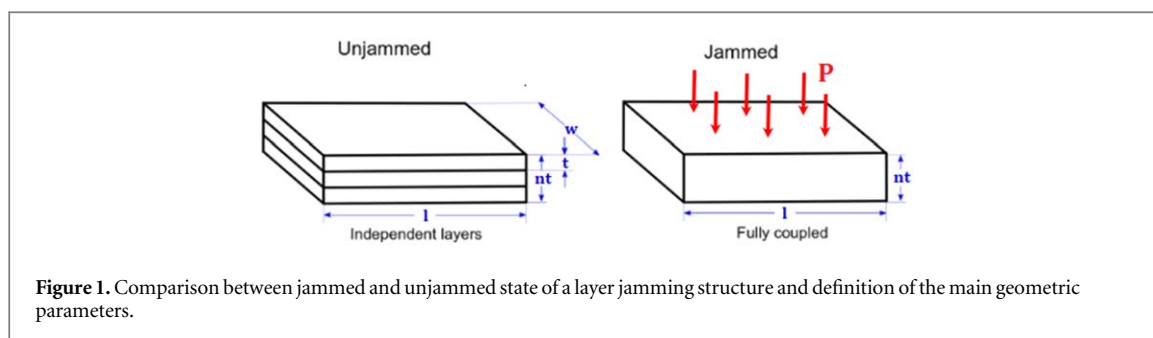
1. Introduction

In recent years, soft robotics has led to a change of paradigm in robotics research and applications, often inspired by the observation of natural structures and behaviors [1]. Thanks to the use of compliant structures and soft materials, soft robots show intrinsic safety, representing a promising solution in several applications where delicate interaction is needed: from industrial grippers [2] to surgical manipulators [3].

While soft devices can adapt to the surrounding environment and guarantee higher dexterity, they are usually limited by the generated output forces and by the sophisticated control strategies needed to compensate instability and oscillation in positioning with respect to traditional rigid devices [4]. The interest on variable stiffness mechanisms stems from these considerations and from the possibility to greatly improve the performances of biomedical devices, wearable technologies, and assistive robots. Stiffness tuning has to be done on-demand and possibly without deformation.

The *jamming phenomenon* is an effective and increasingly common strategy to achieve stiffness tuning in robotics. It refers to a structural interaction induced by the application of a pressure gradient. In particular, it is based on an increase of the overall structure stiffness due to a reduction of the displacement freedom of granular, fiber or layer elements contained in a flexible envelope. Aktas *et al* have proposed a modeling framework to select different jamming structures according to the required performances [5]. Granular elements can achieve 3D stiffening, fiber elements act in 2D, whereas layer elements are better suited for pseudo-planar applications and can achieve a 1D stiffening [6]. This latter is the case, for example, of wearable devices, whose volumes are limited and weight is a major constraint.

Focusing on Layer Jamming, it has been used for different types of applications, ranging from grippers [2, 7, 8] to robotic links [9], and joints [10] for safer human-robot interactions [11], from either force feedback

Figure 1. Comparison between jammed and unjammed state of a layer jamming structure and definition of the main geometric parameters.

[12] or damping gloves [13] to surgical manipulators [14–16], from brakes [17] to shoes and even deformable furniture [18].

Some of these works have already identified some key design parameters [12] or a way to select different jamming materials or sheets patterning [7, 18], whereas other studies proposed the introduction of a dynamic model that allows changing design parameters before validating the final result. However, although researchers have been increasingly interested in this topic [19], most of the works focus on specific applications and a generalized methodology to design layer jamming systems is missing in the current state of the art.

Several hypotheses can be done to model the behavior of layer jamming systems, but to capture them properly, it is essential to recall advanced structural theories and methods that are quite complex and time-consuming. Previous studies showed how experimental characterization or finite element analysis are essential to predict layer jamming systems performances [20, 21], but to use these strategies, most of the design parameters have to be known *a priori*.

However, the design of a layer jamming structure requires several efforts and time (especially in the earliest phases) to identify the most suitable approach to follow, also because of the lack of a schematic guidance to use specified requirements. Therefore, we present the development of a design methodology for developing variable stiffness devices with layer jamming to address these challenges. This stands as a schematic, easy and valid tool useful to the research community for the identification of the most appropriate design alternatives to be considered in the development of a layer jamming system. In order to obtain these features, the presented methodology is based on simplified models, in which both the hypotheses of small displacement and layers inextensibility are assumed. Thus, the target of the tool is not to provide an analytical tool that can predict the behavior of layer jamming systems with high confidence, but to introduce a simplified but generalized design methodology. This is useful both to improve the learning curve of people not familiar with this topic and to speed up the design process of layer jamming systems in the definition of geometry, structure, jamming materials, and other specific parameters.
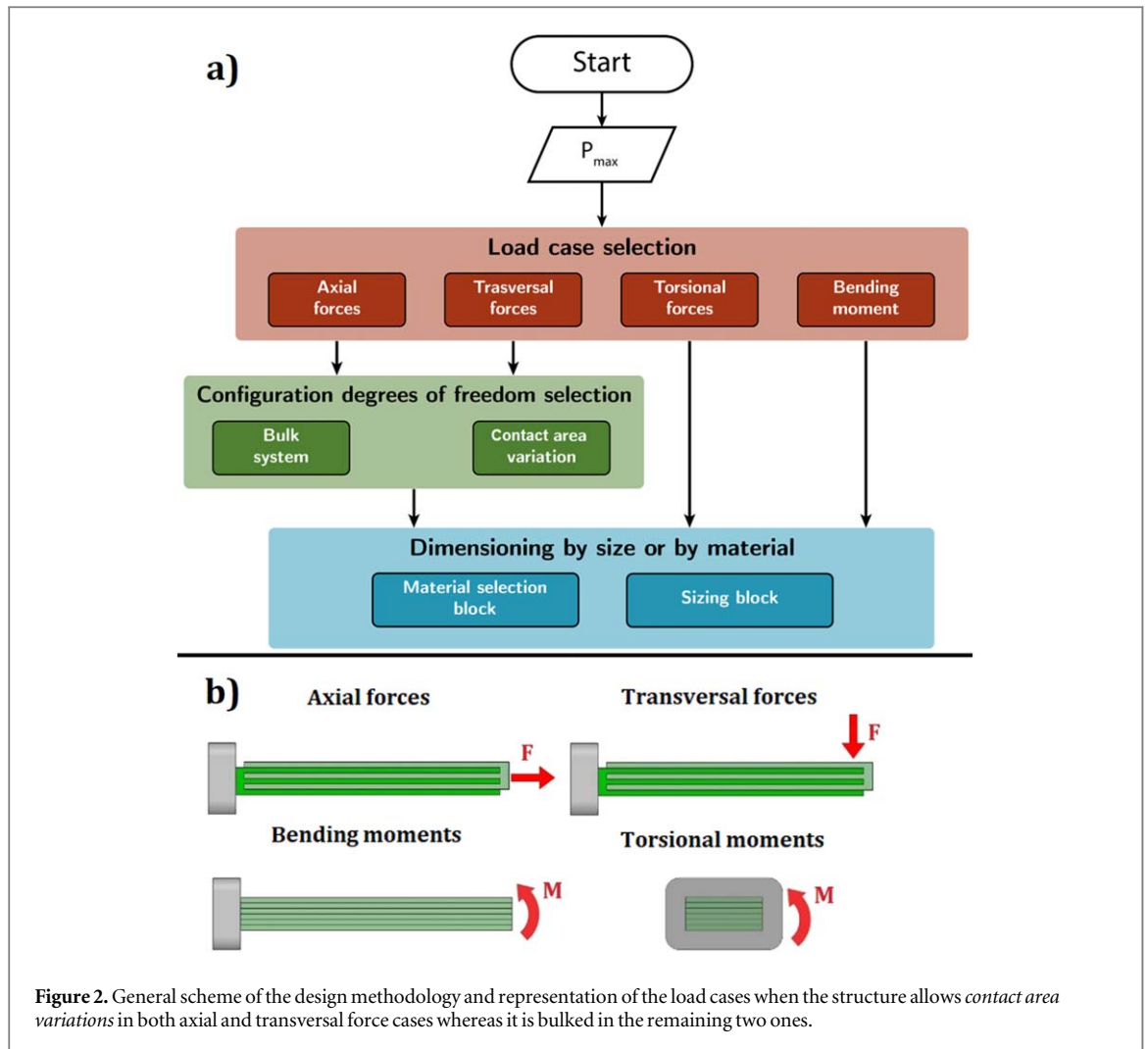
The remainder of this paper is organized as follows: in section 2, the proposed design methodology is reported and described; in section 3, the proposed methodology has been applied to layer jamming systems already presented in literature and the results have been compared to demonstrate its validity; finally, section 4 concludes the paper underlining the applicability of the methodology.

2. Design methodology

The proposed design methodology is valid for layer jamming systems that can be described as cantilever beams. We have chosen this starting point because it represents the most adopted configuration to describe and to use layer jamming systems. However, it is important to note that this is not a major limitation, since the most of the cases that do not use this configuration can be represented as cantilever beams after discretization process. In addition to this, the hypothesis of uniform jamming structures, in which all layers have the same properties, has been done.

Under the specified assumptions, layer jamming system performances can be derived knowing both layers material mechanical properties and geometry. Figure 1 shows how the application of uniform pressure on a system made of n independent layers of length l, width w and thickness t leads to the coupled interaction of layers when the applied loads are below slip thresholds (preslip conditions). This terminology of the geometric parameters is maintained in the following subsections.

In particular, in the methodology here proposed it is possible to select different load case conditions: *axial forces*, *transversal forces*, *bending moments* and *torsional moments*. While the first two load cases have been already addressed in literature, the last two are here proposed for the first time applying the same hypotheses of previous conditions. Moreover, the way the modelling equations are reported in following subsections for all load cases leads to the definition of layer jamming systems design in a step by step process.

Figure 2. General scheme of the design methodology and representation of the load cases when the structure allows *contact area variations* in both axial and transversal force cases whereas it is bulked in the remaining two ones.

2.1. General scheme

Figure 2 reports the general scheme of the proposed generalized design methodology that are described with four main steps, and which are discussed below.

Step 1. The first step concerns the selection of *differential pressure* acting on the system. The main idea underneath the choice is that, even if the pressure input may vary during activation, the maximum range must be taken into account as reference value for the dimensioning. Thus, in the governing equations, the pressure is always a known term.

Step 2. The second step regards the selection of the main load case condition. The choice must fall between the following alternatives: *axial forces*, *transversal forces*, *bending moments* and *torsional moments* (figure 2). Among the possible combinations between these load conditions, we also take into account the case in which both bending moments and transversal forces are applied. This combination is very common and used in several applications in which layer jamming systems are exploited to make variable stiffness actuators. However, as later discussed, this case does not need a separate discussion and can be treated as the case where only transversal forces are applied, simply introducing a different meaning of some parameters.

Step 3. Once the load case has been selected, two alternatives are possible. If the selected load case regards axial forces or transversal forces it is possible to choose between (i) a *bulk configuration*, in which the overall length of the system is always the same before slipping condition, or (ii) a *contact area variation*, in which the jamming transition can be activated at different lengths of the system between the rest and the maximum one. If either bending moments or transversal moments have been selected at the previous step, it is possible to move directly to the next one.
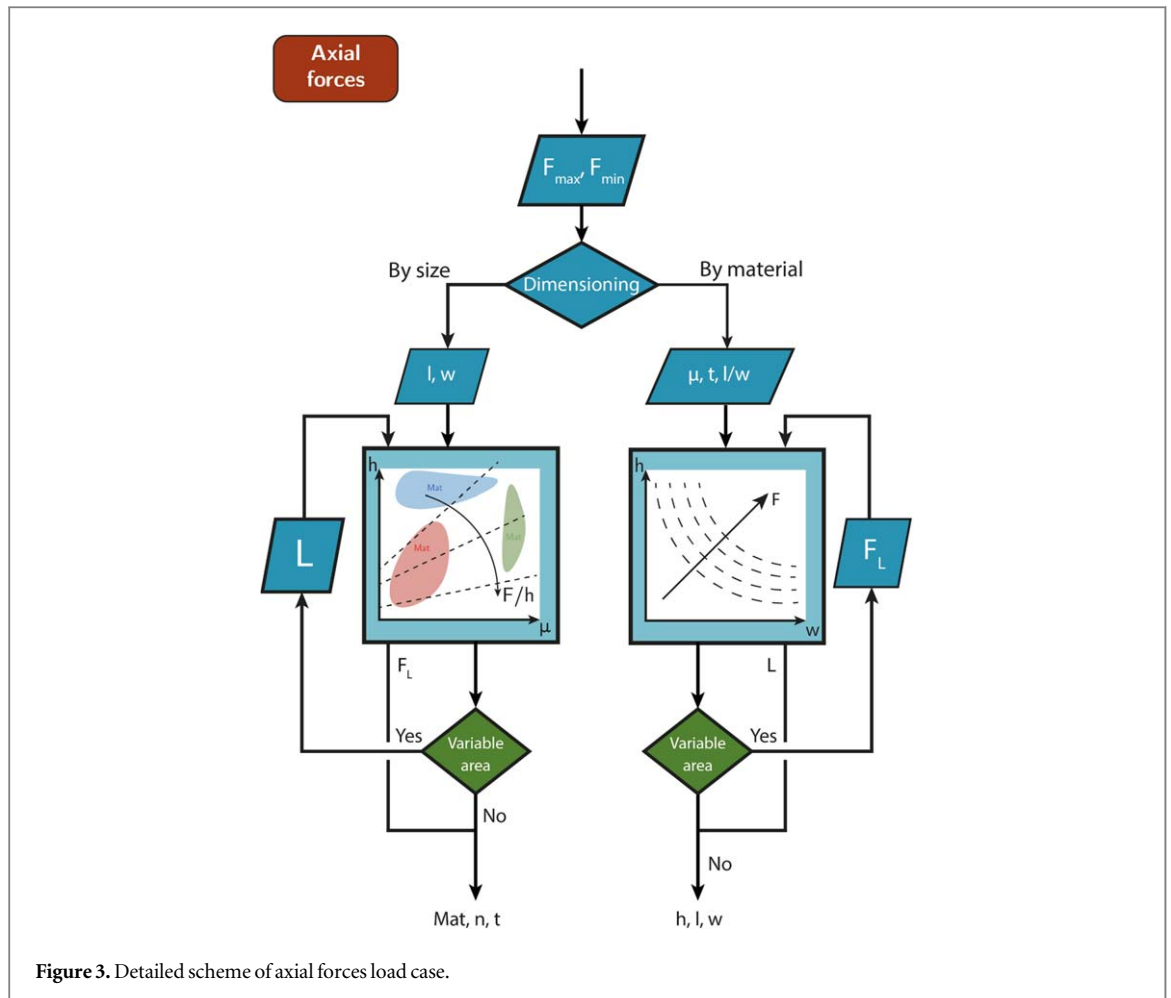
Figure 3. Detailed scheme of axial forces load case.

Step 4. At this step, the design mode can be selected and there are two alternatives: *material selection* or *sizing*. The first case can be used if the size of the system is known *a priori* (e.g. for space limitations) and the layer material has to fit some specifications in terms of slip threshold and stiffness. The second one is the right choice if slip threshold, stiffness and layer material are known, so the sizing of the layers has to be evaluated in order to fit with the required specifications. In both cases, the number of layers is not known beforehand.

2.2. Detailed scheme

Once the correct configuration has been initialized through the selections at *steps* 1–4, the input parameters have to be defined and the output is evaluated through an iterative and interactive process. Both input and output parameters and the governing equations are different according to the configurations selected in the previous steps: axial forces, transversal forces, bending moments and torsional moments load cases are reported in figures 3, 4, 6 and 7, respectively. In order to better clarify how the methodology works, contour graphs are inserted in the detailed schemes. According to the selected case, these graphs show how the unknown terms depend on the known parameters through the model equations that are reported in the following subsections. The methodology becomes more interactive after the selection at *step* 4, where the user is asked to make use of external sources iteratively. If the case of imposed size has been selected (*material selection*), the methodology returns the numerical ranges of the material properties that the user should use to find viable products (for example on an external material library) whose characteristics lie in the provided ranges. On contrary, if the case of imposed material has been chosen (*sizing*), the methodology returns the ranges of functions describing both dimensions and number of layers. In this latter case, the user has to select the values in accordance with the given ranges.

In all cases, the methodology ends with a post-process step in which the user is asked if the performances of the designed layer jamming system have to be evaluated with respect to the remaining load cases. If the answer is yes, some additional parameters are required and must be specified according to the selected load case. The possible load cases are reported and discussed below.
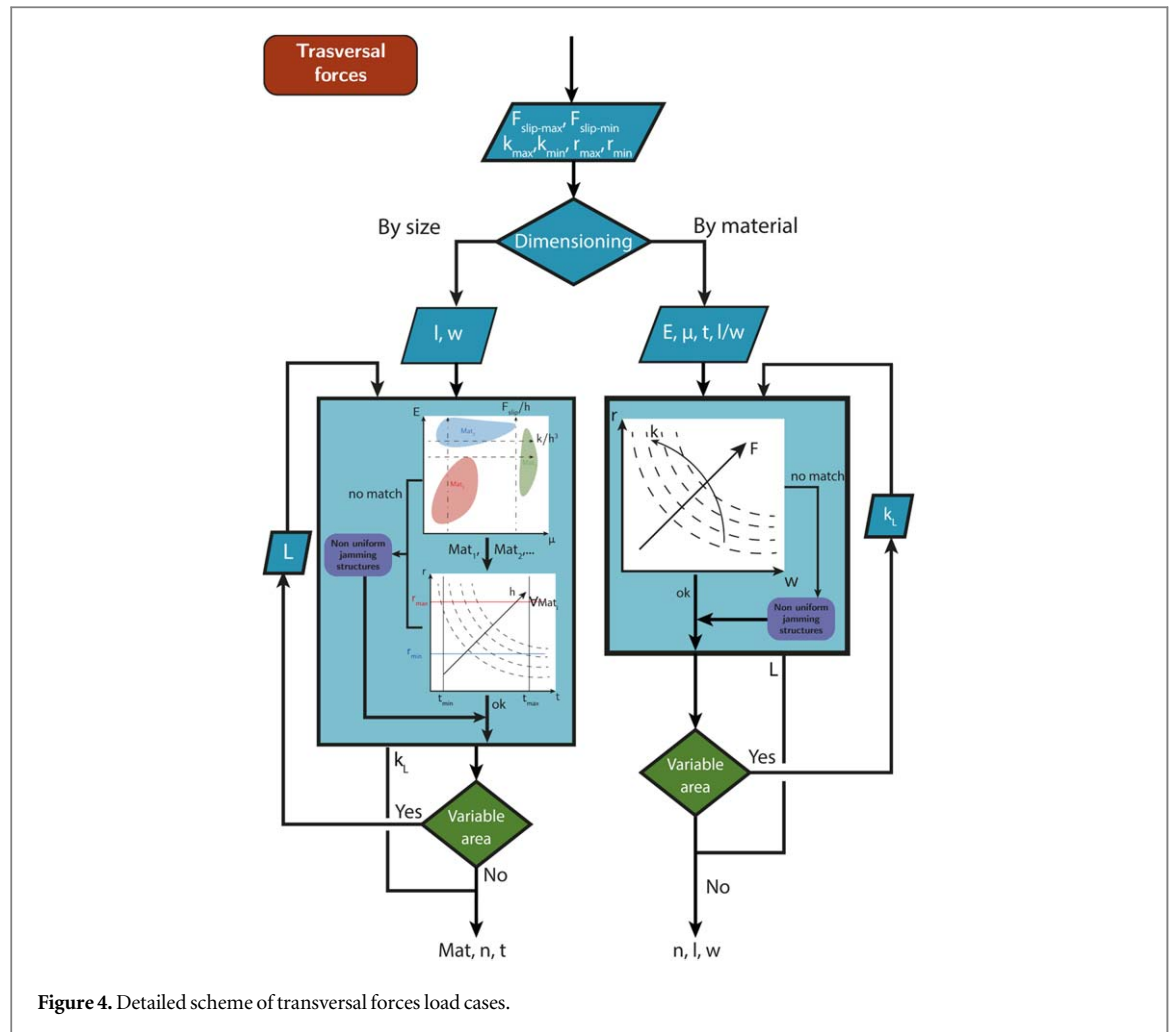
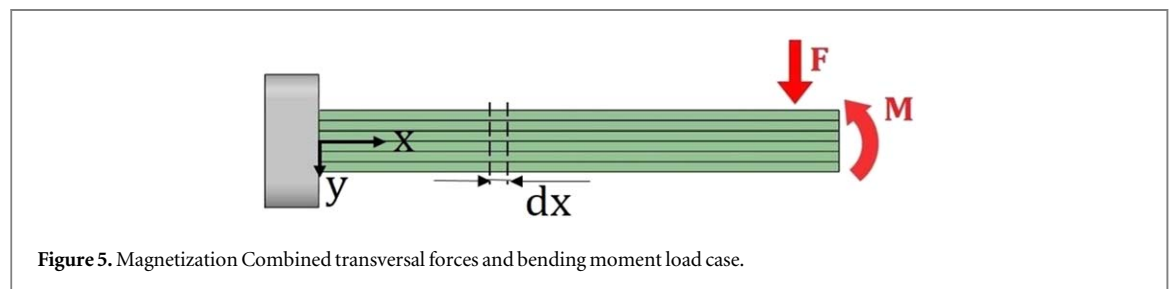**Figure 4.** Detailed scheme of transversal forces load cases.

Figure 5. Magnetization Combined transversal forces and bending moment load case.

2.2.1. Axial forces

For a system made of n layers, with friction coefficient μ on which a differential pressure P is applied (figure 1), according to the equation reported in the study of Kim *et al* [16] the slip force between layers is given by the product between the tangential force induced by the pressure $lw\mu P$ on a single layer and the number of layers (also expressible as the ratio between h and t):

$$F = nlw\mu P = \frac{h}{t}lw\mu P \tag{1}$$

where h is the total height of the system.

At first, the slip forces F_{min} and F_{max}, which define the lower and upper boundary of a range of acceptable performances respectively, must be selected by the user.

2.3. Material selection

In case of *material selection* at *step* 4, the inputs are the layer dimensions l and w, that can be used to evaluate the ratio F/h as:
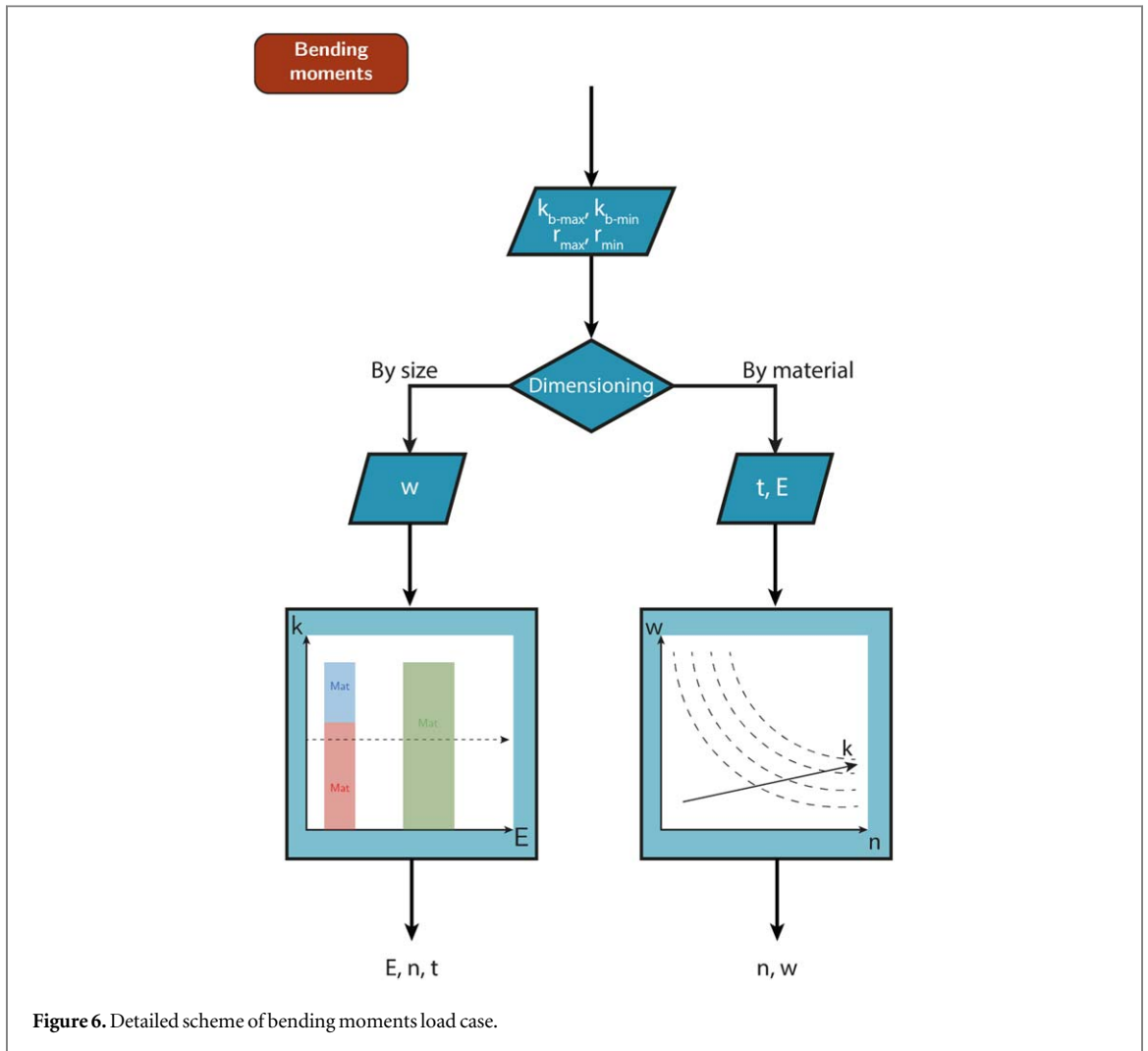
Figure 6. Detailed scheme of bending moments load case.

$$\frac{F}{h} = \frac{\mu}{t} lwP \tag{2}$$

For a guess value of h, the definition of the variation range of this ratio is equivalent to defining a range of acceptable value of the t/μ ratio, which corresponds to a family of materials that fit with the given requirements in terms of both friction coefficient and available layer height. The initial guess of h can be selected as the strictest condition, then the process can be reiterated with different value of h until one or more suitable materials are found. Once the selection process ends, by inserting the specification of the selected material (which also implies a specific number of layers) all the systems parameters are known, and the effective slip force can be evaluated.

If the case of *contact area variation* has been selected at *step* 3, a lower contact area should be taken into account which is given by the product between w and l_{min}, the useful length at which a maximum length of the system L specified by the user corresponds by the relation $l_{min} = 2l - L$. The same modelling equation reported above can be also used to evaluate the slip force at maximum length F_L. The user can accept this result or can reiterate the overall process with a different choice of h to obtain better performances.

2.4. Sizing

In case of *sizing* selection at *step* 4, the inputs are the friction coefficient μ and the height t of the layers. In addition, if the layer dimensions are not known, it is reasonable to impose a specific shape factor l/w of the layers *a priori*, obtained from the optimization of material consumption, for example. In this case, by expressing the length l as function of w by means of the shape factor, the range of acceptable slip forces corresponds to a range of hw^2 values in which a restrictive choice on h (which for a given layer height correspond to a lower number of layers) brings to the need for wider layers. The slip forces are expressed as follow:
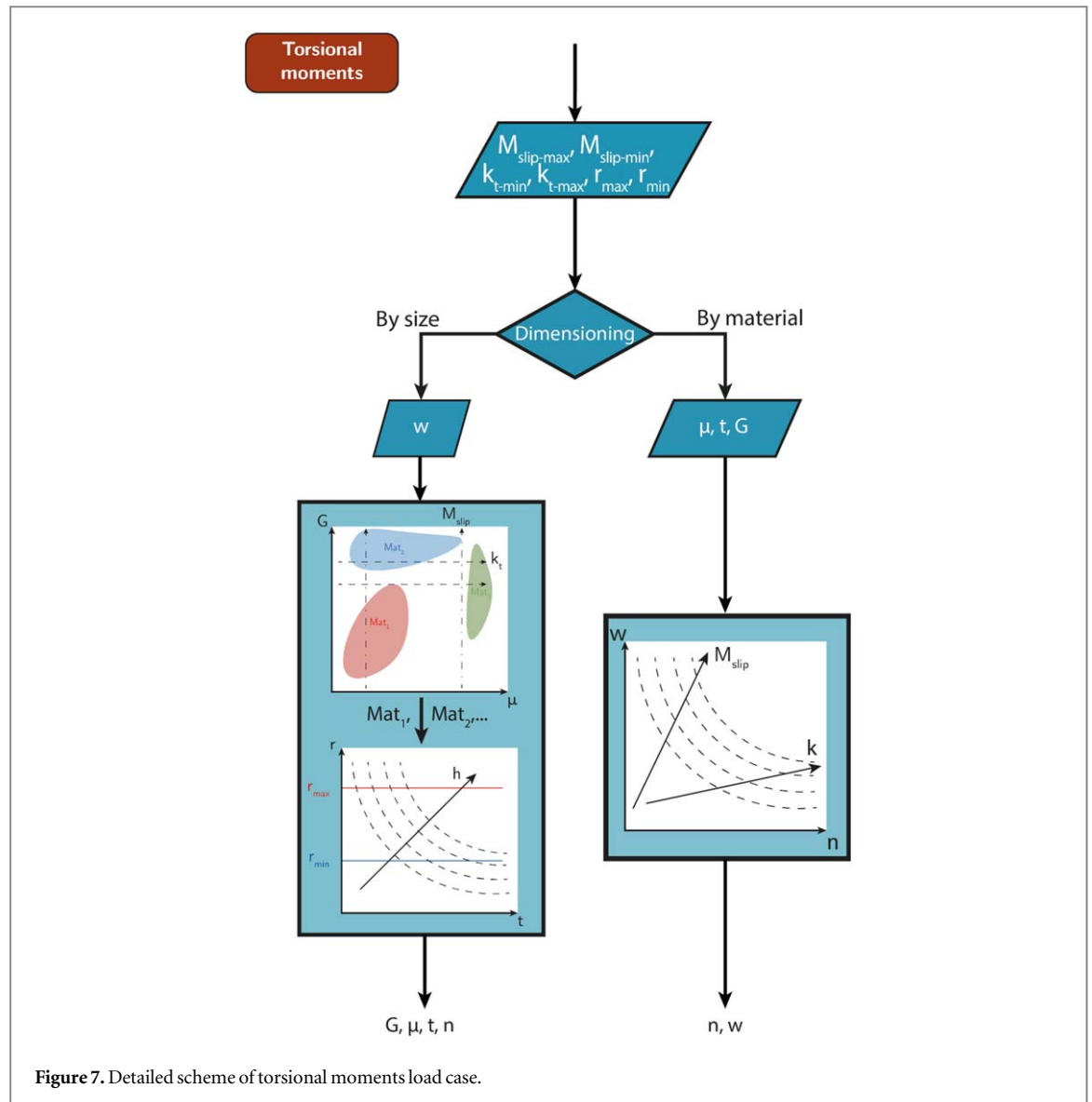
$$F = hw^2 \frac{\mu P}{t} \frac{l}{w} \tag{3}$$

Figure 7. Detailed scheme of torsional moments load case.

The user can balance these two design parameters as necessary to fit with some specific requirements, and once they have been chosen, they must be specified to proceed to the next steps.

If the *contact area variation* has been selected at *step* 3, since the size of the system plays a secondary role with respect to the previous case, the force at maximum length F_L is required as input value in the adoption of the governing equation, as showed before. According to this, the output of the calculation is the maximum length L which fits with the specified input and then, as in the previous case, the design process can end or be entirely repeated.

Finally, if the performances of the designed system have to be evaluated in other load cases, the additional information of Young's modulus and Poisson ratio of the selected layer material have to be specified.

2.4.1. Transversal forces

In case of transversal forces, the differential pressure P prevents the layers from slipping on each other so that the system can be considered as single monolithic block. As a consequence, the unjammed and the jammed state present different area moment of inertia, which are respectively I0 and Ij (see equations (4) and (5)) [20, 22]. This also leads to an increase of the stiffness from k0 to kj, defined as the ratio between applied forces and displacements of the free end (see equations (6) and (7)). The increase of area moment of inertia and stiffness can be expressed as follow:

$$I_0 = \frac{wnt^3}{12} \tag{4}$$

$$I_j = \frac{wn^3t^3}{12} \tag{5}$$

$$k_0 = \frac{3EI_0}{l^3} = \frac{Ewnt^3}{4l^3} \tag{6}$$

$$k_j = \frac{3EI_j}{l^3} = \frac{Ewn^3t^3}{4l^3} \tag{7}$$

where E is the material Young's modulus. The ratio r between k_j and k_0 quantifies the stiffness increment between the jammed and unjammed configurations and it is equal to:

$$r = \frac{k_j}{k_0} = n^2 \tag{8}$$

In this configuration, it is also possible to identify a critical force above what the layers start to slip on each other. This behavior occurs when the shear stress in the structure equals the maximum shear stress (τ_{max}) that can be sustained by friction (μP):

$$\tau_{max} = \mu P = \frac{3V_{max}}{2A} \tag{9}$$

where V_{max} is the maximum shear force and $A = ntw$ is the cross-section area. By substituting the value of the applied force to V_{max}, it is possible to obtain the slip force as follows:

$$V_{max} = F \tag{10}$$

$$F_{slip} = \frac{2\mu PA}{3} = \frac{2}{3}\mu Phw = \frac{2}{3}\mu Pntw \tag{11}$$

Several works [20, 21, 23] highlighted how once the critical conditions are exceeded, the layers slide progressively and the relationship between applied forces and displacements becomes nonlinear. Then, once all layers are sliding, they are fully decoupled and the overall behavior is again linear, similar to what happens below the critical value, but with a different stiffness (depending on the dynamic friction coefficient). Therefore, the relationship between forces and displacements of layer jamming systems is usually decomposed into three regions: (i) elastic, (ii) transition, and (iii) plastic.

Under the simplified hypotheses on which the methodology is based, it is not possible to capture the nonlinear behavior of the transition region. Therefore, the force versus displacement relationship is given by two regions: (i) the linear one, described by the stiffness k_j, and (ii) the plastic one, described by the stiffness k_0. In this case, the user has to define the lower and upper boundaries of the range of acceptable stiffnesses, slip forces and jamming ratio, which are respectively: k_{j_min} and k_{j_max}, F_{slip_min} and F_{slip_max}, r_{min} and r_{max}.

2.5. Material selection

The inputs are the layer dimensions l and w. The definition of the layer material features has to be done step by step. Once the guess value h has been defined, imposing the values of minimum and maximum slip forces, it is possible to identify a range of acceptable values of the ratio F_{slip}/h, which is equivalent to define a range of acceptable frictional coefficients μ. This ratio is expressed as follows:

$$\frac{F_{slip}}{h} = \mu\frac{2wP}{3} \tag{12}$$

Then, imposing the minimum and maximum stiffnesses, it is possible to identify a range of acceptable values of the ratio k_j/h^3, which is equivalent to define a range of acceptable Young's moduli E, and it is defined as follows:

$$\frac{k_j}{h^3} = E\frac{w}{4l^3} \tag{13}$$

It is possible to notice that these two steps lead to the definition of a rectangular area in the first plot reported in figure 4, where the choice of a greater value of h corresponds to both a reduction and a translation toward the axis origin of the area of acceptable materials. For each material compliant with the constraints imposed in the two previous steps, the minimum and the maximum values of jamming ratio have to be taken into account. The methodology returns the minimum and maximum number of layers, thanks to the relation expressed in equation (8). Consequently, for each acceptable material found, the user has to check the availability of layers with height t, which ensures to obtain the selected h with an acceptable number of layers.

If the *contact area variation* has been selected at *step 3*, the user has to define the maximum length L. Then, it is possible to overlook the change of area moment of inertia due to the sliding among layers, and the

methodology returns the corresponding stiffness k_L. According to the adopted theory, the slip threshold is not affected by the length change.

The procedure can be entirely repeated with different overall height values until the given results match with the user requirements. If no possible solutions are identified, a fast analysis of the results obtained at the single steps can be useful to find better alternatives in the adoption of non-uniform jamming structures. If the material selection has been restricted mostly because of the range of acceptable Young's modulus, non-uniform strategies such as the jamming sandwich structures (which are composed of layers of one type between two layers on another one) [24] or the use of parallel-guided structures [25] can be adopted in order to fit with the required stiffnesses. On contrary, if the friction coefficient range has mostly influenced the material selection, the threshold between non-slip and slip conditions can be incremented using a non-uniform strategy in which a layer of one type is placed between layers of another one.

2.6. Sizing

The inputs are the friction coefficient μ, the Young's modulus E, the height t, and the shape factor l/w of the selected layers. By imposing the minimum and maximum of the slip force, a range of acceptable values for the product nw is identified, whereas by imposing the minimum and maximum of the stiffness, the range of acceptable values for the ratio n^3/w^2 can be obtained, as expressed by the following equations:

$$nw = \frac{3F_{slip}}{2t\mu P} \tag{14}$$

$$\frac{n^3}{w^2} = \frac{4k_j \frac{l^3}{w}}{Et^3} \tag{15}$$

Once the selected values of number and width of layers have been specified, if the *contact area variation* has been selected at *step 3*, the user needs to define the stiffness at maximum length k_L and the methodology returns the corresponding value of L. If the result is not acceptable, the procedure can be reiterated starting from the previous step. As in the previous case, the adoption of non-uniform jamming structure can be an alternative approach in case the output of the methodology does not match same specific user requirements.

Finally, the user is asked to specify the Poisson ratio of the selected layer material as additional information, in order to evaluate the performances of the designed system in other load cases.

2.7. Combined transversal forces and bending moment load case

The same approach reported in the previous section can be used if both bending moments and transversal forces are applied. In this case, considering both the reference system and the loads showed in figure 5, the following equations hold:

$$d\varphi = \frac{M_{tot}}{EI}dx = \frac{F(l-x) - M}{EI}dx \tag{16}$$

$$df = x d\varphi \tag{17}$$

where $d\varphi$ is the angle between two sections of the beam at infinitesimal length dx in the deformed configuration. The relationship between loads and displacements of the free end f can be then expressed as:

$$f = \int_0^l \frac{F(l-x)x - Mx}{EI}dx = \left(F - \frac{3M}{2l}\right)\frac{l^3}{3EI} \tag{18}$$

Assuming the stiffness can be evaluated as follows:

$$k_j = \frac{\left(F - \frac{3M}{2l}\right)}{f} = \frac{3EI}{l^3} = \frac{Ewh^3}{4l^3} \tag{19}$$

it is possible to obtain the same results reported in equation (7). For what concerns the slip threshold, the presence of a bending moment does not affect the shear force, so equation (11) still holds. In summary, the design methodology is still valid, but the values entered as k_{j_min} and k_{j_max} must be considered as equivalent stiffnesses representing the combined load, as shown in figure 5.

This configuration can be adopted when, for example, a layer jamming system is combined with an actuator and transversal forces are applied. In these cases, the actuator effect can be taken into account by means of a moment opposite to the external transversal forces. Several applications, such as variable stiffness grippers and manipulators can be modelled in this way.

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moment opposite to the external transversal forces. Several applications, such as variable stiffness grippers and manipulators can be modelled in this way.

2.7.1. Bending moments

Under the same simplified hypotheses adopted for both axial and transversal forces, the modelling equations in case of bending moments are:

$$k_b = \frac{Ewh^3}{12} \tag{20}$$

$$r = \frac{k_b}{k_{b_0}} = n^2 \tag{21}$$

The value k_b represents the relation between the bending moment that acts on the system and the assumed curvature, thus it does not depend on the length of the structure. No shear forces act on the system, hence in this case no information about the slip and non-slip region can be obtained.

As a preliminary information, the user is required to set the lower and upper boundaries of the range of acceptable bending stiffnesses and jamming ratio, which are defined through $k_{b\_\min}$, $k_{b\_\max}$, $r_{\min}$ and $r_{\max}$, respectively.

2.8. Material selection

The user has to specify the width w of the layers as input. Then for a given guess value of the overall height h, imposing the minimum and maximum bending stiffnesses in equation (20), the range of acceptable Young's moduli E is obtained.

For the acceptable materials, the user has to select the layer height t that returns the specified overall height h, once multiplied for a number n in the range of acceptable values obtained by the conditions on the minimum and maximum jamming ratio (see equation (21)). As in previous cases, this process can be repeated iteratively until the obtained results fits with the user requirements.

2.9. Sizing

The inputs are the Young's modulus E and the layer height t of the selected layer. In this case, the range of acceptable stiffnesses corresponds to a range of acceptable wn^3 values through equation (20). The n value has to be selected in the range of acceptable values given by the conditions on the minimum and maximum jamming ratio, as in the previous case. Then the layer width w can be evaluated.

Finally, if the performances of the designed system have to be evaluated in other load cases, the user needs to define the additional inputs of selected material: the friction coefficient, the Poisson ratio, and the layers length.

2.9.1. Torsional moments

For a cantilever beam with rectangular section, considering the simplifying hypotheses adopted so far and the additional one of $w \gg h$, the governing equations in torsional moments load case are:

$$k_{t_j} = \frac{Gwh^3}{3} \tag{22}$$

$$M_{slip} = \frac{hw^2 \mu P}{3} \tag{23}$$

$$r = \frac{k_{t_j}}{k_{t_0}} = n^2 \tag{24}$$

The value k_{t_j} represents the relation between the torsional moment which acts on the system and the resulting rotation angle of the free end. As previously described in transversal forces load case, equation (23) can be obtained equating the shear force on the external layer and the maximum shear force that can be sustained by friction.

In this case, the user has to define the lower and upper boundaries of the range of acceptable torsional stiffnesses, slip moments and jamming ratio, which are respectively: $k_{t_j \min}$ and $k_{t_j \max}$, $M_{slip\_\min}$ and $M_{slip\_\max}$, $r_{\min}$ and $r_{\max}$.

2.10. Material selection

This design process has to be done step by step. As proposed for the transversal moments load case, for a given guess value of the overall height h, imposing the minimum and maximum slip moments, the range of acceptable friction coefficients is obtained, as shown in the following equation:

$$\frac{M_{slip}}{h} = \mu \frac{w^2 P}{3} \tag{25}$$

Then, imposing the minimum and maximum torsional stiffnesses, it is possible to identify a range of acceptable k_{t_j}/h^3 ratios:

$$\frac{k_{t_j}}{h^3} = G\frac{w}{3} \tag{26}$$

or equivalently a range for the shear modulus $G = E[2(1 + \nu)]$, where E is the Young's modulus and ν is the Poisson ratio.

As in the transversal forces load case, these two steps lead to the definition of a rectangular area (shown in the first graph reported in figure 7), in which a high value of h brings to both a reduction of the area of acceptable materials and its translation toward the axis origin. Then, through equation (24), the methodology returns the minimum and maximum number of layers, which set the range of acceptable values of the jamming ratio. With this result, the user can check the availability for each acceptable material found, considering the layer height t that ensures to obtain the selected h with an acceptable number of layers. As in previous cases, the procedure can be reiterated with different guess values of h, if obtained results are not acceptable.

2.11. Sizing

The friction coefficient μ, the shear modulus G and the layer height t of the selected layer have to be specified. A range of acceptable nw^2 can be identified imposing the minimum and maximum values for the slip moment:

$$nw^2 = \frac{3M_{slip}}{t\mu P} \tag{27}$$

while the range of acceptable $n^3 w$ can be obtained imposing the minimum and maximum values for the torsional stiffnesses:

$$n^3 w = \frac{3k_{t_j}}{Gt^3} \tag{28}$$

Once the values of the selected n and w have been specified by the user, the Young's modulus of the selected layer material and the layers length are required as additional information, in order to evaluate the performances of the designed system in other load cases.

3. Application of the methodology

In this section, the proposed methodology is applied to layer jamming systems already developed and characterized, found in literature. Since the vast majority of layer jamming systems refers to transversal forces load case, the proposed methodology has been applied to this load case mode. In addition, it was not possible to cover the other three load cases because of the lack of works in which the designed systems have been characterized numerically. Two different works were considered to verify the applicability of our methodology. The main idea is to start from the system performances as presented in the characterization sections of the selected papers, and then to use the proposed methodology in either design by size or design by material mode to compare our results against the specific choice made in the paper. In the first case, the layer dimensions are compared to the actual one, whereas in the second case, the range of acceptable layer material properties are compared. In the first work, the designed layer jamming systems have been characterized at different pressures with a fixed number of layers. In the second work, both variable pressure and variable number of layers are considered. In addition, this last work provides the opportunity to prove that systems not directly referable to a cantilever beam configuration can be still represented with this simplified model through a discretization process. The application of the proposed methodology to these two works shows how the methodology can work under different conditions and especially in two different design modes.

The first analysed system is the Layer Jamming cantilever beam structure introduced and characterized by Acevedo *et al* [21]. In this work the force versus displacement relationship of a layer jamming system made of two materials, namely Delrin and glued playing cards, is reported at different pressure inputs (30, 50 and 70 kPa). We have applied the methodology in design by material (sizing) mode at the system made of 2 Delrin layers. The numerical values of the actual layer material parameters reported in the selected paper are summarized in table 1.

Once the differential pressure has been set (starting from the lowest value), the transversal forces load case has been selected at *step 2*. Then, *bulk system* configuration and design by material have been selected at *steps 3* and *4*. At this point, the values of k_{j_min} and k_{j_max}, F_{slip_min} and F_{slip_max} have been evaluated by averaging the

Table 1. Delrin layers parameters [21].

Length l [mm]	WIDTH W[MM]	Height t [mm]	Young modulus E [GPa]	Friction coefficient
30	20	0.79	2.9	0.3

Table 2. Application of the methodology on the case of Delrin layers [21].

Input			Model output		Experimental value
P [MPa]	$F_{slip\ min}$; $F_{slip\ max}$ [N]	$k_{j\ min}$; $k_{j\ max}$ [Nmm^{-1}]	w_{min}; w_{max} (nw) [mm]	w_{min}; w_{max} (n^3/w^2) [mm]	w [mm]
0.03	0.180; 0.220	1.8; 2.2	18.95; 23.05	19.65; 24.36	20
0.05	0.315; 0.385	1.8; 2.2	19.65; 24.07	19.65; 24.36	
0.07	0.405; 0.495	1.8; 2.2	18.30; 22.37	19.65; 24.36	

Table 3. Copy paper layers parameters [22].

Half-Length l [mm]	Width w [mm]	Young modulus E [GPa]	Friction coefficient
65	50	6	0.65

results of the three tests for each pressure input estimated by the graphs reported in the source article [21], considering a central value $\pm$10%. Finally, the required layer parameters of friction coefficient, Young's modulus, height and shape factor *l/w* have been specified. The obtained *w* range of acceptability has been derived by the *nw* and n^3/w^2 ones considering 2 (actual value) as number of layers. To validate the methodology, this range has been compared to the actual value of width equal to 20 mm.

All inputs and obtained outputs are reported in table 2, together with the value used in the real case. For the sake of clarity in table 2 cells whose values are used as input for the model have white background; dark gray is used for the cells reporting the model output; in light gray the real values taken from the experimental tests. This allows a direct comparison btween model prediction and experimental results. The same color code has been used also in table 4.

From the results reported in table 2, it is possible to verify how the ranges of acceptable layer widths match the actual value of the real case for each of the three pressure inputs, confirming that the numerical results obtained through the proposed methodology are reliable in this application case, where a low number of layers and different pressure inputs are used.

In order to verify the applicability of the methodology also for a higher number of layers, we have then considered the layer jamming system in three point bending configuration presented and characterized by Narang *et al* [22] In this case second, before starting the analysis, it is necessary to translate the actual configuration of the system into the one implemented by the methodology by a discretization process. Taking one half of the entire three point bending structure and then turning it upside-down, the loaded end is replaced with a clamp and the supported end is now free and loaded with half of the actual applied force. In this way an equivalent cantilever beam structure is obtained where, with respect to the actual conditions, half of the overall length between the supports and half of the forces have to be taken into account.

In this case, the used material is copy paper and the values of the relative parameters are reported in table 3. Since no height of the layers is reported in the selected paper, we have assumed the value of 0.12 mm measured on an available same item. Both results at different pressure inputs and different number of layers have been considered.

Firstly, the differential pressure has been set to the values of the different cases. Then, the transversal forces load case and the *bulk system* option have been selected at *step* 2 and 3. Finally, at *step 4* the design by size mode has been chosen.

As in previous case, the values of k_{j_min} and k_{j_max}, F_{slip_min} and F_{slip_max} have been estimated by the plots reported in the paper [22], considering a central value $\pm$10%, and both the required layer dimensions length and width have been specified. Once the overall height has been selected according to the number of layers of the different cases, acceptable values range for both the friction coefficients and Young's moduli have been compared with the actual values. All results are reported in table 4.

Table 4. Application of the methodology on the case of copy paper layers [22].

Input				Model output		Experimental values	
P [MPa]	n	$F_{slip\ min}$; $F_{slip\ max}$ [N]	$k_{j\ min}$; $k_{j\ max}$ [Nmm^{-1}]	μ_{min}; μ_{max}	E_{min}; E_{max} [GPa]	μ	E [GPa]
0.024	20	1.125; 1.375	3.60; 4.40	0.585; 0.716	5.72; 6.99		
0.047	20	2.025; 2.475	3.60; 4.40	0.539; 0.658	5.72; 6.99		
0.071	20	3.060; 3.340	3.60; 4.40	0.538; 0.659	5.72; 6.99	0.65	6
0.071	15	2.295; 2.805	1.60; 1.98	0.639; 0.657	6.00; 7.47		
0.071	10	1.620; 1.980	0.45; 0.55	0.570; 0.690	5.72; 6.99		

The results derived by the application of the proposed methodology show how the actual material parameters are compatible with the range of acceptable values obtained, where both different pressure and different number of layers have been considered.

The two applications here reported demonstrate that if a layer jamming system design has to satisfy some specific requirements, the proposed methodology returns immediately the range of acceptability of the key design parameters either in terms of geometry or material properties. This potentially reduces considerably both the time and the cost of the initial phases of the design process of a layer jamming structure, often based on trial and error.

Moreover, as shown, the outcomes can be strictly numerically valid even though the proposed methodology is based on simplified hypotheses. Regarding this last point, it is important to underline that high accuracy of the input parameters is required to obtain reliable outputs. However, it is not always possible to satisfy this condition as usually happens in the evaluation of the material properties and especially of the friction coefficients. Therefore, while in design by size mode the choice of a very reliable material library is crucial, in design by material mode materials correlated with accurate datasheet should be preferred.

4. Conclusions

In this paper a simplified yet generalized methodology to design uniform layer jamming structures under specific requirements has been presented. We demonstrated that the execution of design choices in the reported order can lead to the identification of the best numerical alternatives that can be follow to satisfy application requirements straightforwardly and in short time.

The main goal of this work is to provide the research community with a fast and easy-to-use tool which can be useful especially during the first approach of layer jamming system design. The proposed methodology is able to analyze different load configurations, namely axial forces, transversal forces, bending moments and torsional moments. Furthermore, it has been showed how the transversal forces load case can also be used to design layer jamming systems subject to both transversal forces and bending moments.

The effectiveness of the proposed methodology has been proved through its application to layer jamming structures reported in literature, both in design by size and in design by material mode for the transversal forces load case. In this way, we have demonstrated that despite the simplifying hypotheses, the methodology can lead to accurate numerical results in the considered load case. The obtained information can be very useful to define the directions to follow during the first phases of the design process of layer jamming systems independently from the load configuration, provided that reliable values for input parameters are available.

Finally, we have made a Matlab script available to facilitate the implementation and the usage of the proposed methodology. It can be found in supplementary material, hoping that it can be the starting point for further developments in line with the spirit of cooperation on which this work is based.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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