Numerical modeling of a reduced scale mooring line experimental investigation for load attenuation evaluation

Eduardo Gibbon Rosa[1], Marcelo Maia Rocha[1]

[1]*Dept. of Civil Engineering, Federal University of Rio Grande do Sul - UFRGS*
99 Osvaldo Aranha Ave, 90035-190, Porto Alegre – Rio Grande do Sul, Brazil
eduardo.gibbon@ufrgs.br, mmrocha@ufrgs.br

Abstract. Oil platforms are migrating into deep waters, where the maintenance of its position represents an engineering challenge. It has become usual to adopt mooring systems composed of chains that extend from the floating unit to the foundation element and, along its length, have an embedded segment in the seabed, shaped as an inverse catenary, capable of attenuating the acting forces. Several studies have been conducted to improve the understanding of soil-chain interaction and estimate the expected attenuation level according to each problem's characteristics. Investigations in this area can be developed under experimental approach, normally on reduced scale, or under numerical approach, which allows the simulation of a wide range of scenarios. Therewith, the present work aims to simulate experimental tests in 1:40 geometric scale that reproduce the segment of a mooring line embedded in soil, using a numerical finite element model built in a commercial software (ANSYS). The model considers soil elements as a perfect elastoplastic material, chain elements as an elastic material with tension only behavior and pair of target and contact elements which simulates the interface between soil and chain. The obtained results are discussed by means of stress distribution in soil and percentages of load attenuation.

Keywords: offshore platform, mooring line, load attenuation.

1 Introduction

The use of mooring system may be defined as an ancient procedure, considering the initial development of navigation and the need to maintain a vessel in a determined position, once the equilibrium with the external forces was stablished. Since then, the concept expanded to offshore oil platforms, which make use of mooring systems normally composed of mooring lines, made of steel chains and/or polyester cable, connecting the floating unit itself in the upper end, where the environmental loads act, to a foundation device in the lower end, responsible for major load transfer to the soil.

More recently, the oil exploration units have been progressively distancing from the continent, not only reaching greater water depths but demanding enhancements in the understanding of how loads are transferred through the mooring lines. Along its length, this element presents two different conditions: submerged in water and embedded in soil; the latter is subject of several investigations and studies (see Vivatrat et al. [1], Degenkamp and Dutta [2], Neubecker and Randolph [3,4], Neubecker and O'Neill [5], Liu et al. [6], Rocha et al. [7], Rosa and Rocha [8], for instance), due to the soil-chain interaction existence, which leads to a more complex analysis of normal and tangential forces induced in the interface between materials.

Neubecker and Randolph [3] state that, after the foundation device is installed and the pre-load application starts, the anchor chain induces cutting and sliding at the zone of contact with the soil, which, in contrast, opposes the movement and induces the formation of the traditional inverse catenary configuration recurrently observed in related problems. Besides the modification of the embedded mooring line shape, the reactions acting on soil-chain interface are responsible for load attenuation, that is, the force applied in the dip-down point (DDP, point of embedment in the soil) does not fully matches the force observed in the foundation element. More specifically, the mathematical approach proposed by Vivatrat et al. [1] and Degenkamp and Dutta [2] suggests that the tangential component of reaction is the one responsible for the load decrease while the normal component reaction molds the inverse catenary shape, influencing the foundation load capacity according to the angle formed in the connection between chain and anchor device.

One of the greatest challenges concerning offshore floating units mooring systems consists in its huge dimensions, what makes difficult, not to say impossible, to conduct experimental investigations on full scale; therefore, studies like Sampa et al. [9], performing reduced scale tests, or Braun et al. [10], developing numerical models, should be highlighted. Additionally, previous work published by Rosa and Rocha [8] mentioned how the determination of load attenuation range related to a specific situation would be very valuable to companies in the industry, as it could lead to less expensive system design; the authors introduced a first version of a 3D finite element model, built with the aid of ANSYS software, where some validation was presented based on Degenkamp and Dutta [2] and Li et al. [11] data. In order to expand and testify the numerical simulation capacity, the current paper presents the model application to Rocha et al. [7] study, revising how the experimental investigations were built and discussing the modifications and input data needed for the numerical model.

2 Experimental setup and numerical model description

In an attempt to determine the load attenuation provided by mooring line embedded in soil, Rocha et al. [7] developed a series of reduced scale tests, adopting a geometric scale of 1:40, which aims to represent a typical design case, proposed by Petrobras, following the line of research developed in partnership between the company and UFRGS. To assess the problem, the authors built an experimental apparatus consisting of an acrylic tank, whose dimensions are 1.52×0.8×0.24 m (length, depth and width, respectively), a metallic rail that enables mooring line suspension and load application, supports for accommodating weights and load cells for measuring the force at the anchor point.

According to Rocha et al. [7], the tests were conducted based on load and unload cycles: first, the loading was progressively increased, with increments of 10 N, from 0 to 140 N; afterwards, the load was progressively withdrawn, with decrements of 10 N, from 140 to 0 N; throughout the tests, the loading and unloading cycles were performed for different angles of force application at the free end, in a range of 5º, from 20º to 55º in relation to the vertical axis of the tank.

Altogether, the authors provide the data and results of 12 tests carried out, which differ, in short, by the type of clay used (Clay A or Clay B), anchoring point depth, average soil undrained shear strength (S_u), load attenuation level and the relationship between tangential and normal soil component reactions. Among the tests, those identified as Test 2, Test 3, Test 11 and Test 12 stand out, including an illustration of estimated embedded inverse catenary shape, being, therefore, subjects of comparison in the current paper.

Furthermore, it is worth to emphasize an important conclusion stablished by the authors: due to the observed results, it may be an oversimplified approach to admit a direct and linear relationship between the tangential and normal reaction along the chain, since, according to the applied load level, there may be greater or lesser mobilization of each component. In addition, a dependence of this relationship to S_u is demonstrated: the greater this parameter, the greater the contribution of tangential (or frictional) reactions.

The material's characteristics adopted in experimental investigations must be cited, since they provide the input data for the numerical model. Thus, the studless mooring chain used by Rocha et al. [7] has a nominal diameter of 3mm and a unit mass of 160 g/m; the tests aim to simulate the real case of a chain with a nominal diameter of 120mm, on a scale of 1:40, and a unit mass of 280 kg/m, on a scale of 1:1600, with a certain deviation from the necessary value, considered as irrelevant due to the little influence of the self-weight for these dimensions. When it comes to soil modeling, two mixtures were produced with proportions of 90% kaolin and 10% bentonite and moisture content of 100% and 120%, identifying Clay A and Clay B, respectively. The authors report that the two clays were submitted to the Mini Vane test to obtain the undrained strength profile along the depth of the tank (see Tab. 1); it was observed a better representation of Clay B for the typical clay soils of the Brazilian coast.

Table 1. Undrained soil shear strength regarding to each experimental setup and numerically simulated.

Parameter	Clay A		Clay B		Unity
	Test 2	Test 3	Test 11	Test 12	
S_u	0,508	0,507	1,873	1,856	kN/m²

From the numerical model point of view, the problem of load attenuation in a mooring line system can be understood by three main elements: soil, chain and anchoring device. For simplification, this last component is represented as a fixed support and is responsible for providing the horizontal and vertical reactions which represent the resulting attenuated load (F_a) reaching and acting on the foundation element.

In this present version of the study, the soil continues to be assumed with a perfect elastoplastic behavior, based on what is identified as the Extended Drucker-Prager Model (EDP), natively available in the software ANSYS; this model is used in detriment of the Classical Drucker-Prager Model due to the compatibility with the finite element choose to represent the soil, that is, SOLID185.

Considering the magnitude scale of the loads and the dimensions of the mooring chains that normally represent the segment embedded in the soil, the behavior of this material is assumed to be purely elastic and the finite elements identified as LINK180 were choose. According to the software manual, the LINK180 is suitable for modeling structural elements with uniaxial behavior, such as cables, for example.

The mechanical behavior that governs the soil-current interface originates from Coulomb's Law of Friction. To simulate the interface between soil and chain, pairs of elements identified as CONTA177 and TARGE170 were used, which establish a type of contact classified as "line-to-surface". Basically, when using this feature, there are restrictions on the penetration of the elements associated with the contacts (mooring line) in the target elements (soil), which, together with the slide restrictions, aim to simulate the mobilization of normal and tangential strength of the soil.

One of the most important factors to be incorporated in the model is the configuration of the mooring line embedded in soil, since, as previously exposed, in the process of implementing the system, the development of an inverse catenary format is expected in this region. In general, it is possible to affirm that this complex mechanism is influenced not only by soil and chain characteristics but also by the magnitude and direction of the applied load.

Ideally, an analysis that covers from the moment of anchor penetration to the pre-load application that induces the inverse catenary would present more accuracy to capture all the nuances expected in the problem. However, in order to reduce the computational cost involved in this type of analysis, the construction of the model already considers the equilibrium configuration of the inverse catenary, with coordinates obtained from reference studies. From Rocha et al. [7], the inverse catenaries shown in Fig. 1 were incorporated in the model through equal length segments, resulting in the finite element mesh illustrated in Fig. 2.

The application of the boundary conditions begins in the simulation of the total vertical and lateral geostatic stresses, according to soil specific weight and anchor point depth. In terms of restraints and support conditions, due to the intrinsic characteristics of the problem, symmetry is used in relation to the XY plane, which allows a considerable gain in computational performance, since only half of the problem needs to be modeled. Naturally, in order to maintain the stiffness characteristics of the linear element used to simulate the anchor line, half of the cross-sectional area must be adopted as an input property; it is worth mentioning that the same division is made for the request force applied at the free end of the anchor line. Finally, displacement restrictions are addressed to the problem: vertical displacement restraints (Uy = 0) are applied to all nodes of the ground elements on face parallel to XZ plane, lateral displacement restraints (Ux = 0) are applied to all nodes of the ground elements on face parallel to YZ plane and lateral displacement restraints (Uz = 0) are applied to all nodes of the ground elements on face parallel to XY plane. After applying the boundary conditions, the model is able to receive the load applied to the free end of the anchor line.

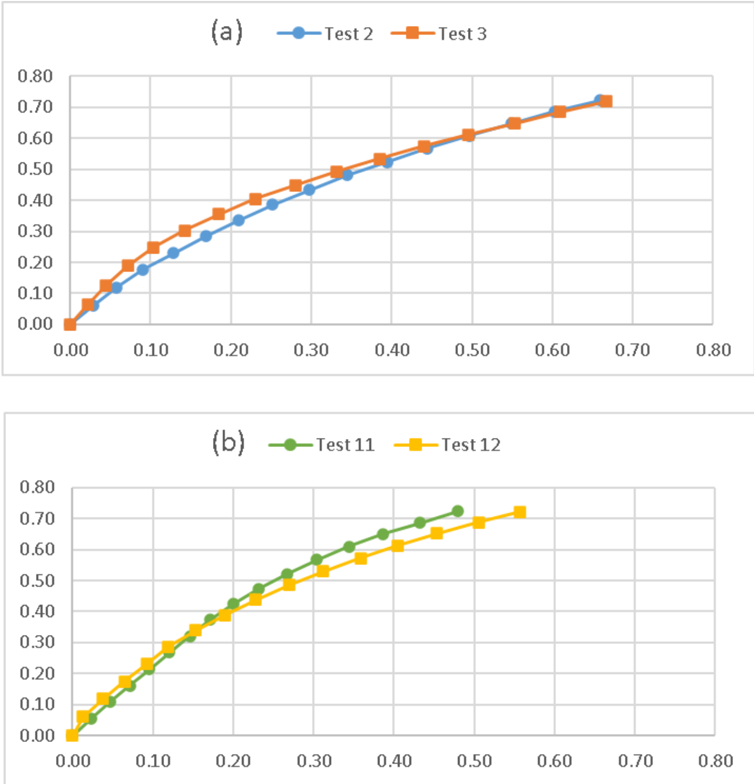

Figure 1. Inverse catenary representation: (a) Tests 2 and 3, (b) Tests 11 and 12.

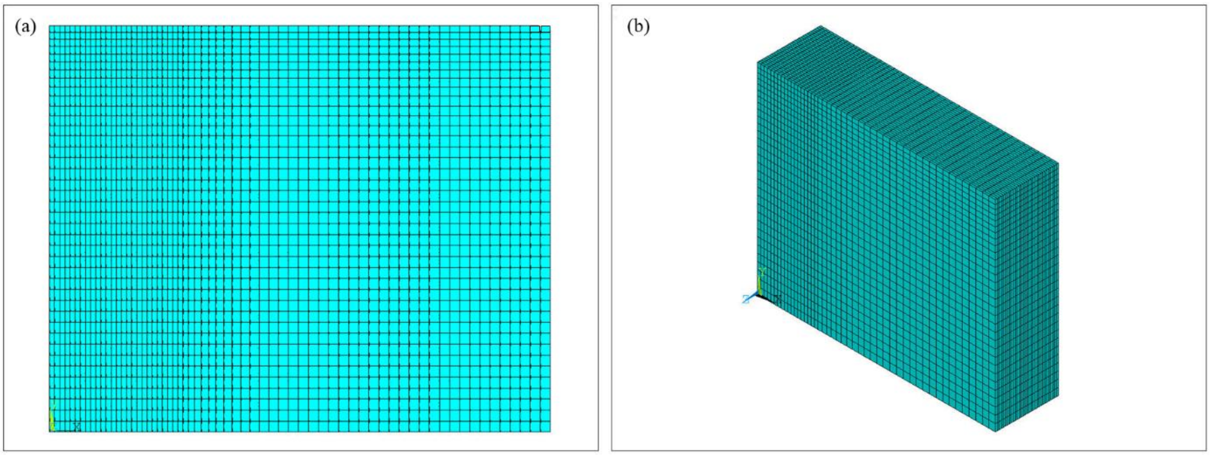

Figure 2. Front view (a) and isometric perspective (b) of mesh typical configuration.

3 Input data and analysis results

Besides some of the input data relative to soil strength and inverse catenary shape of the embedded chain previously cited, others parameters must still be provided. For the numerical model, it was adopted saturated Clays A and B with specific weight (γ_w) of 15.4 kN/m³, Poisson's ratio (ν_s) equal to 0.49, while friction (φ) and dilatancy (ψ) angles equal to zero are assumed, aiming to simulate undrained loading conditions. The relationship between modulus of elasticity and soil resistance (E_s/S_u) was taken as 500.

Regarding the properties of the anchor chain, the nominal equivalent diameter is equal to 5,09 mm, with Young modulus (E_c) estimated at 2.10e8 kPa and Poisson's ratio (ν_c) equal to 0.3. In addition, the friction coefficient (μ) equal to 0.5 was assumed as representative for the soil-chain interface.

On each of the four scenarios (Test 2, Test 3, Test 11 and Test 12), the force at the anchor point (F_a) was taken from the ANSYS post-processing tools, as the Tab. 2 below summarizes the results obtained. It should be noted that, for load attenuation level evaluation, it is considered the relation $1 - F_a/F_0$, in terms of percentual values.

Table 2. Resultant forces at anchoring point for experimental and numerical scenarios.

Identification	Resultant force from Rocha et. al [7]	Resultant force from current work	Load attenuation from Rocha et. al [7]	Load attenuation from current work
Test 2	109 N	108 N	22%	23%
Test 3	113 N	105 N	19%	25%
Test 11	77 N	76 N	45%	46%
Test 12	84 N	83 N	40%	41%

To complement the set of results brought in Tab. 2, the behavior of the stresses developed in the soil due to the disturbance caused by the anchor chain, in terms of Von Mises equivalent stress, is illustrated in the sequence of figures that follows (Fig. 3 to Fig. 6):

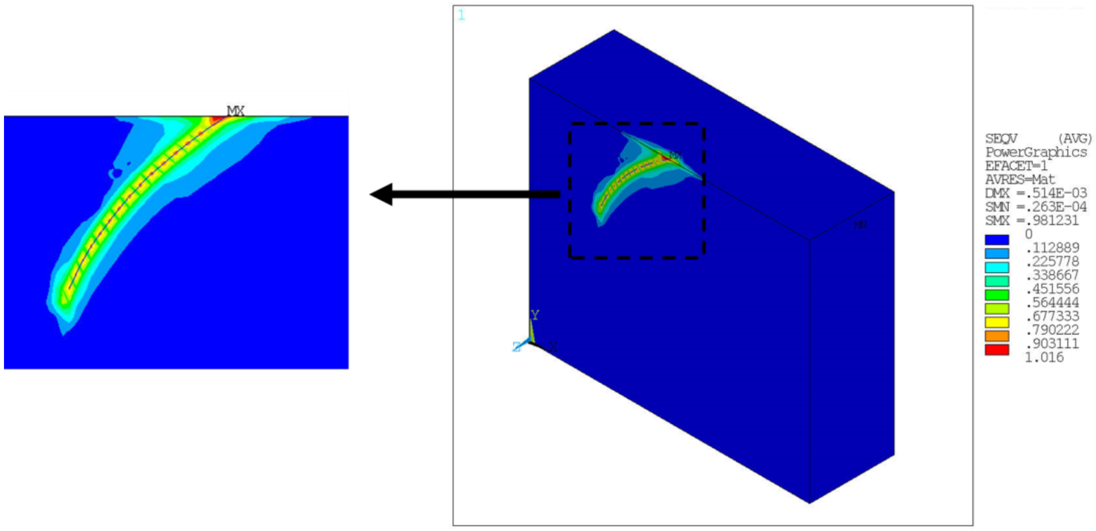

Figure 3. Von Mises equivalent stress distribution for Test 2, in kPa.

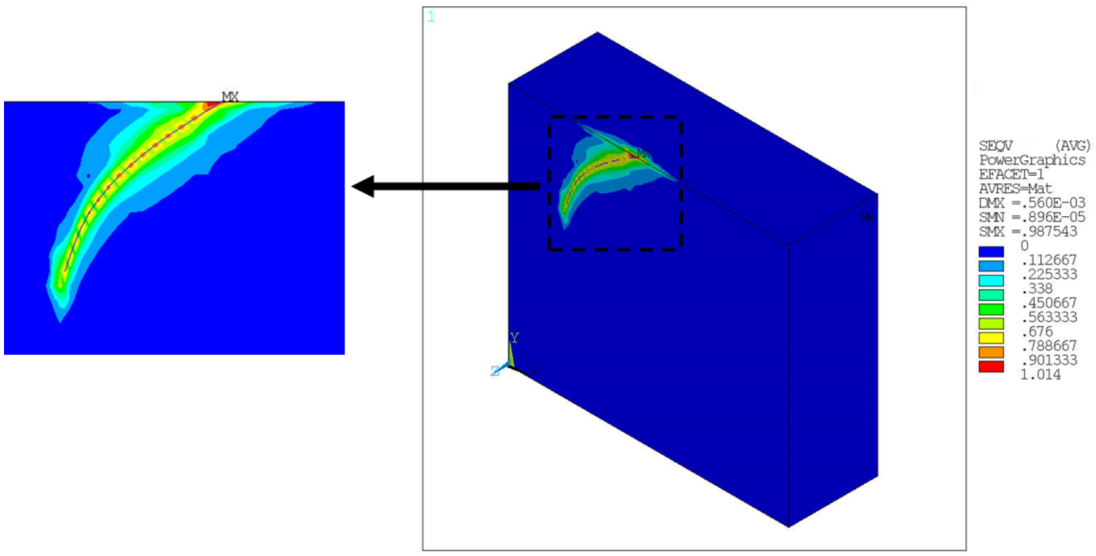

Figure 4. Von Mises equivalent stress distribution for Test 3, in kPa.

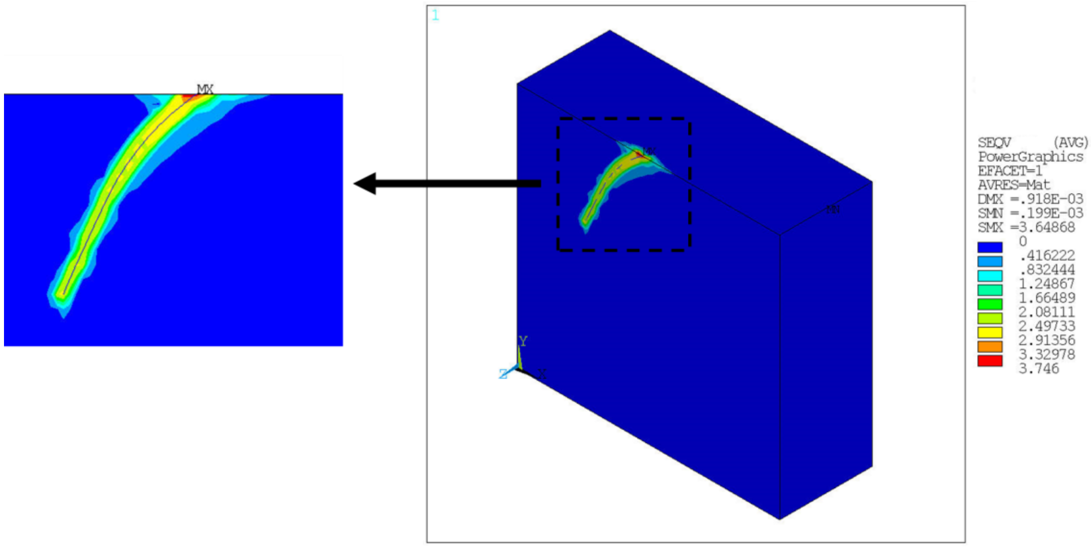

Figure 5. Von Mises equivalent stress distribution for Test 11, in kPa.

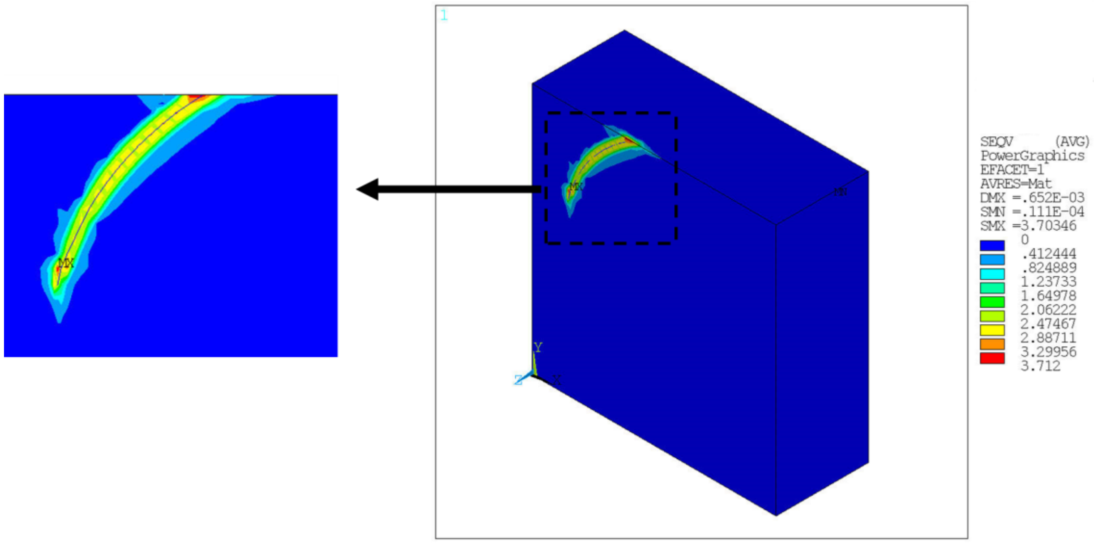

Figure 6. Von Mises equivalent stress distribution for Test 12, in kPa.

4 Conclusions

The current paper describes the application of finite element numerical model in the ANSYS software in order to simulate the mechanisms involved in the soil-chain interaction related to mooring systems. A first version of the model was described by Rosa and Rocha [8] and some improvements have been incorporated, such as the mesh discretization, for example. The central idea is to continue the validation and verification tests of the numerical model, so that its effectiveness in determining the levels of attenuation is proven adequate as a design tool.

The attenuation percentages obtained for all cases in the numerical models created showed satisfactory approximation with the results provided by Rocha et al. [7], with percentages between 30 and 24% for the first pair of tests (compared to 19 and 22% of the reference) and 46 and 43% for the second pair of trials (compared to 40 and 45% for the reference). These results corroborate the initial expectation that the more resistant the soil, the greater its attenuation capacity.

As for the stress disturbance caused in the soil, for the set of figures shown (Fig. 3 to Fig. 6), it is observed in the pair of models identified as Test 2 and Test 3, where the soil has characteristics of lower strength, and in the pair named as Test 11 and Test 12, a disturbance of the entire region adjacent to the mooring line, with greater concentration on the upper end, close to the load application. When drawing a parallel between the attenuation percentages shown in Tab. 2 and the Von Mises equivalent stress contours, it is observed that the most favorable profiles are those in which lower mobilization along the chain occurs (Test 11 and Test 12), indicating that when the opposite happens, as in Test 2 and Test 3, greater load transmission is allowed between the free and restrained end.

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