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Astrup Fearnley Museum: Structural Design and Detailing of the Stayed Masts

Sudarshan KRISHNAN, Ph.D.

Associate Professor, Chair of Building Performance Program,
School of Architecture, University of Illinois at Urbana-Champaign,
117 Temple Buell Hall, 611 Taft Drive, Champaign, IL 61820, USA.
skrishnn@illinois.edu

Abstract

The Astrup Fearnley Museum uses the modern equivalent of nautical sailboats masts, that structural designers refer to as stayed masts or stayed columns. The designers of the museum found unique ways to harmoniously integrate stayed masts with roofs, glass façades, and other components of the building.

Stayed masts consist of a solid or tubular core with prestressed steel rods or cables attached to them with the help of intermediate transverse cross-arms. Prestressed stays augment a mast's stiffness and compressive strength while allowing for a lightweight core. The solution is a strikingly innovative enhancement to conventional masts – both architecturally and structurally.

Mast configurations in the Astrup Fearnley museum range from simple to intricate. Some masts go from ground up to the roof rising several stories, while others are suspended from an intermediate floor to hold the roof. Some are designed to resist compression loads only while others are designed to withstand the effects of wind and lateral forces. Different materials and cross-sectional shapes for the core have added delight to the innovative forms. This paper describes the innovative stayed mast configurations, interesting connection detailing, and unique structural and stability behaviour using the case-study of the Astrup Fearnley Museum.

Keywords: masts, museum, stayed masts, stability behavior, detailing

1. Introduction

Masts -- tall compression members, play a crucial role in supporting high tensile forces from connecting membranes or cables, ensuring the safe transfer of loads to foundations. They can be made in different forms such as tubular, built-up, latticed, stayed, flying, or tower-like structures. In this chapter, we focus specifically on unstayed tall slender columns, collectively referred to as "masts," before delving into the intricacies of prestressed stayed masts, which we'll simply denote as "stayed masts."

The demand for lightweight yet expansive structures has spurred the development of stayed masts. Beyond their structural utility, they've become sought after for their architectural flair. Tall buildings with lofty spaces often benefit from these slender masts, reducing core sizes while bolstering strength through prestressed stays. Stayed masts find diverse applications, serving as primary compression elements in tensioned-membrane structures, vertical struts in cable domes, diagonal braces in lateral load-resistant frames, and even as deployable booms in space missions.

Astrup Fearnley Museum in Oslo is a special structure showcasing the elegance of stayed masts while utilizing the structural merits. The material selection is strategic. Wood is used as a reference to boats and the slender stayed masts evoke the maritime character of the Oslo harbour (Area 116, 2011).

Figure 1: View of the Astrup Fearnley Museum, Oslo, Norway. (Courtesy: RPBW)

2. Mast Configurations

The museum showcases a range of planar masts, including single, double, triple, and five cross-arm configurations, as well as simple tubular masts. Aside from their structural advantages, the stayed masts were designed to reflect Norway's maritime heritage. The tallest stayed mast, measuring 25 meters in height and approximately 500 mm x 260 mm x 60 mm thick, extends across multiple stories. The cross-sections of the stayed masts are elliptical hollow structural steel, while the unstayed masts are circular. Clever orientation of the core strengthens the weak axis along the shorter face, utilizing a network of cross-arms and prestressed stayed cables.

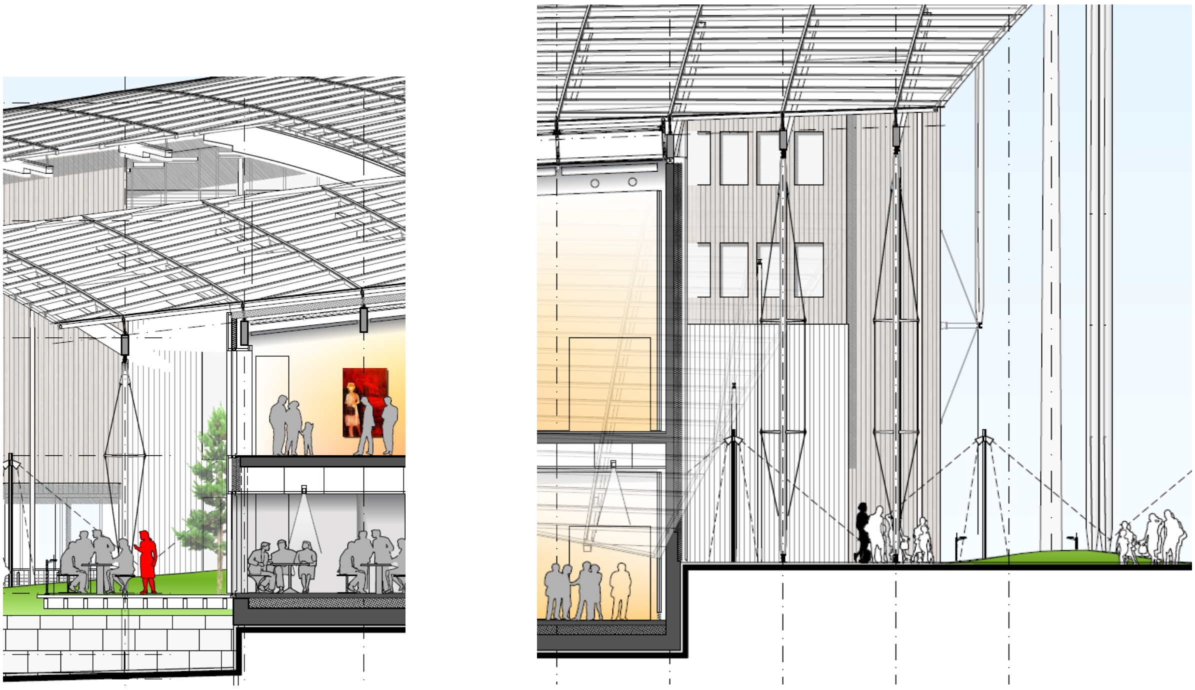

Figure 2: Single cross-arm and double cross-arm stayed mast configurations as used in the Astrup Fearnley Museum, Oslo, Norway. (The diagram was cropped to emphasize only the essential features of stayed masts using a drawing provided by RPBW)

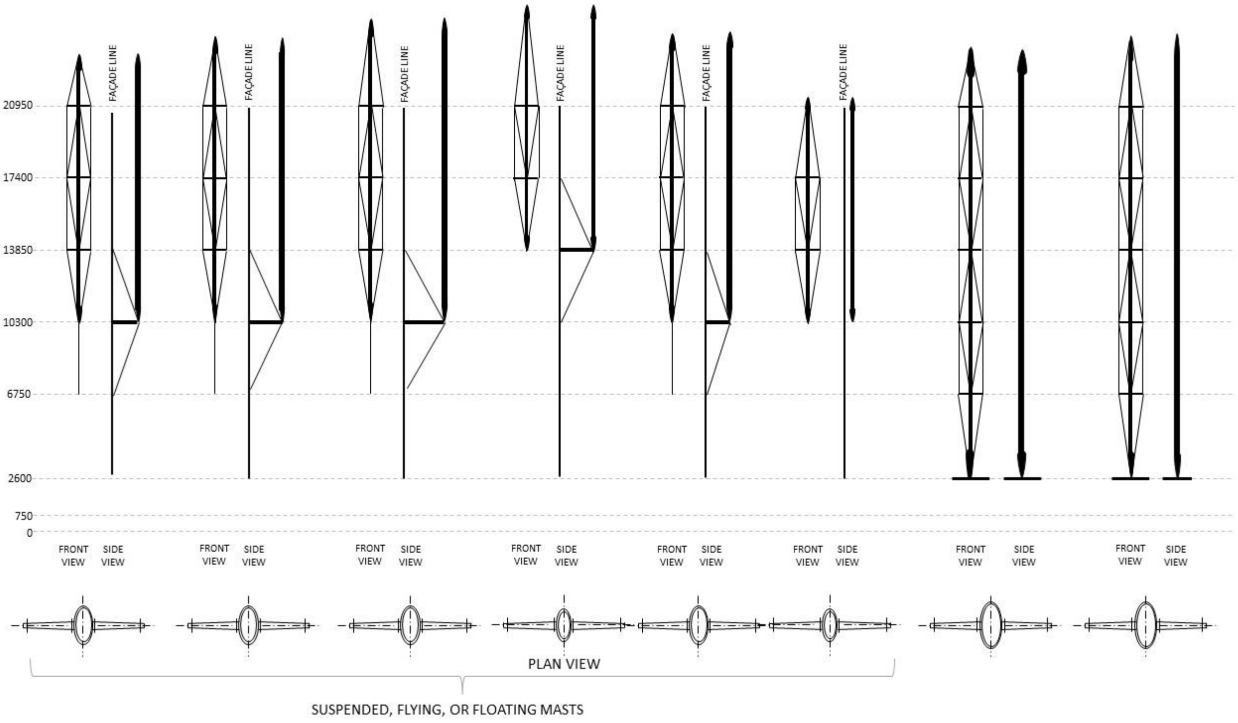

Figure 3: The variety of stayed mast configurations used in the Astrup Fearnley Museum, Oslo, Norway. (The diagram was redrawn to emphasize only the essential features of stayed masts using the drawings provided by RPBW)

3. Connection Detailing

Masts are commonly hinged at both ends and braced against lateral displacements, either through direct attachment via floor or roof diaphragm action, or through membranes and cables connected to mast ends. Connection detailing between mast members ensures proper load transfer, reducing stress concentrations and improving structural stability. Additionally, the Astrup Fearnley Museum features several suspended masts supported ingeniously by a system of steel rods and members extending horizontally from the walls, as depicted in Fig. 4. Thick plates welded into the steel tube core at mast ends facilitate the connection of cables/rods.

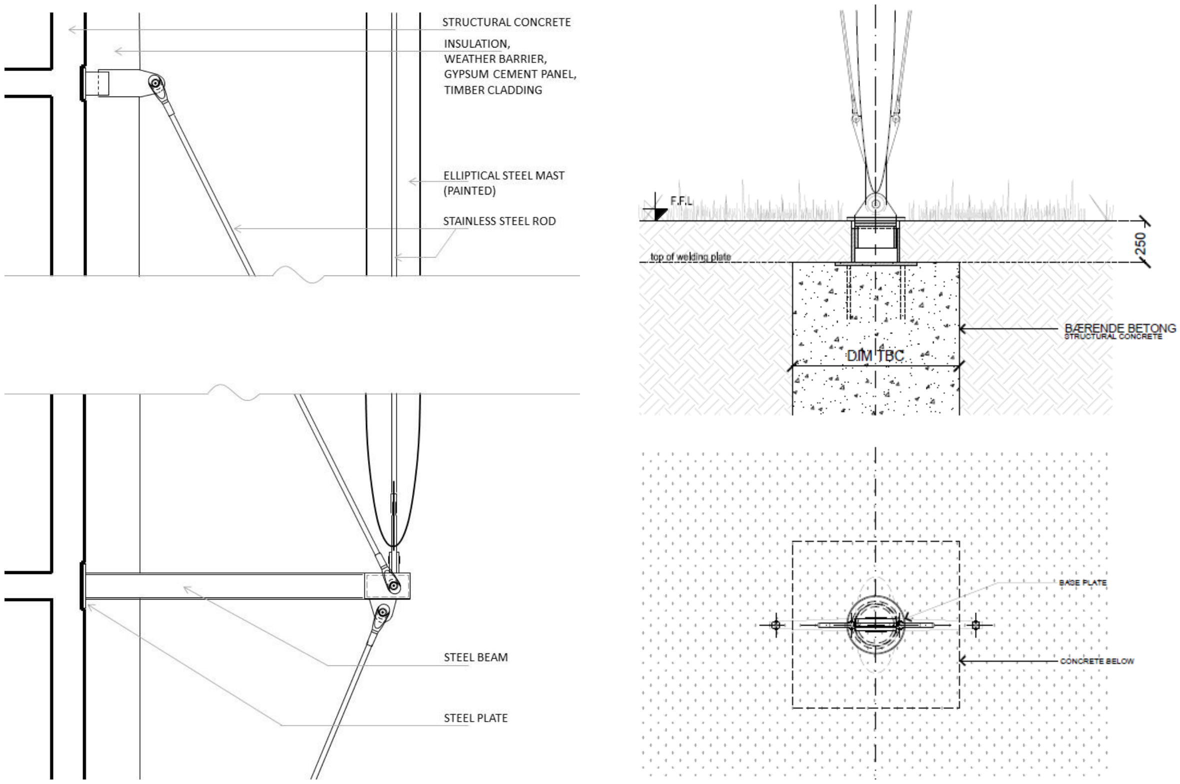

Figure 4: (a) Connection detailing of suspended masts in the Astrup Fearnley Museum (b) Connection detailing at the base (The diagram was redrawn to emphasize only the essential features of stayed masts using the drawings provided by RPBW)

4. Cable/Rod Pretensioning

Structural designers must understand the impact of cable prestraining on mast performance under axial load. The initial pretension force applied to the stays determines the mast's ultimate axial strength. Excessive prestrain can weaken the column by overcompressing the central core beyond the external load's impact. Insufficient prestrain may cause cable slackening as the external load compresses the column core, reducing cable tension. While some loss of cable tension due to column shortening is inevitable and should be factored into analysis, complete loss of tension under small axial loads is unacceptable, leading to premature column failure. Design should ensure that stays remain taut across varying loads, ensuring $P_{sl} > P_{cr}$, where P_{sl} is the load causing full cable slackening, and P_{cr} is the column buckling strength. Assigning an appropriate level of prestress is crucial to maintain adequate tension in the stays consistently. Optimum prestrain, corresponding to the highest buckling load, should be considered. (Gurfinkel and Krishnan, 2017)

5. Limit States and Strength Enhancement

For design purposes, three distinct stages of loading should be considered: (1) at initial cable prestressing, (2) during service, and (3) at failure. For well-designed masts, i.e., those that are adequately prestressed, cable slackening will not occur prematurely. As such, stayed masts must be designed for two limit loads: (1) Load at which the core yields: There is a possibility for the core to yield under a force N_y caused by a load $P_\mathrm{y} < P_\mathrm{cr}$, and (2) Load at which the mast buckles: In case of tall slender masts, buckling would be the prevalent cause for failure and as such the most important limit state. For a given solution to be acceptable, N_{cr} must not exceed the upper limit N_y, and $P_{cr} > N_E$. For low cable prestrains, total slackening may result due to loss of cable tension as the applied compression load increases. This is indicated as AVOID range in the plot shown in Fig. 5.

The column core alone defines the lower and upper limits of a stayed column's compressive strength as shown. The two limits would be given by its buckling strength, $N_E = (\pi/L)^2EI$, and its yield strength, $N_y = A_cF_y$, assuming that the tube is slender enough that $N_E < N_y$. The difference between the quantities N_y and N_E is the maximum amount of strengthening that can be added to the tube by transforming it into a cable-stayed column. The larger the difference between the two values, the greater the strength enhancement that may be achieved by adding cable-stays.

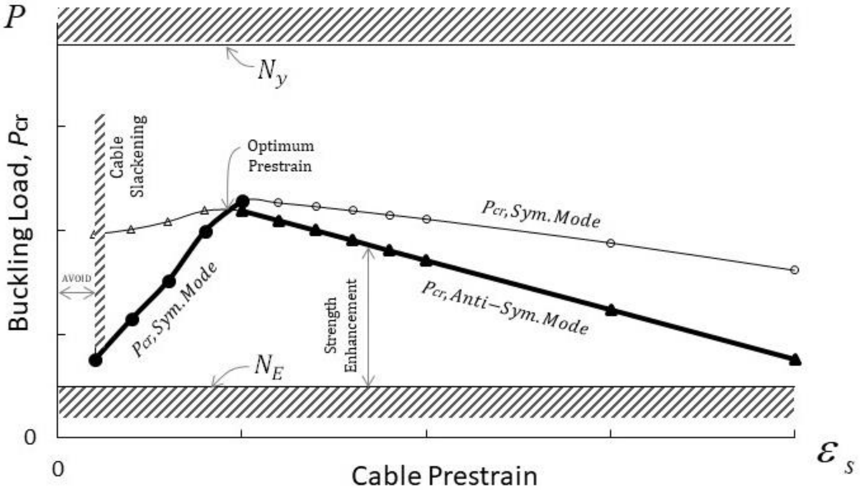

Figure 5: Limit States and Strength Enhancement

Obviously, if a steel tube were stubby enough that $N_E > N_y$, it would not warrant the use of stay cables. An equation for strength enhancement is also defined by Gurfinkel and Krishnan (2017) as the ratio of the difference between the nominal compression strengths of a stayed and unstayed tube to the nominal compression strength of the tube alone.

6. Mast Stability

At system level, stability may be a matter of concern when local failure of connecting elements compromise the structural integrity of a mast. Design of structures must ensure that failure of membranes or cables do not compromise the stability of masts and thereby avert a full system collapse. Redundancy may be provided in the form of additional cables that connect mast heads to prevent any large displacements due to local failure of connecting elements to the masts.

Masts are designed mainly for axial loads (gravity and prestress) while some may be loaded in bending due to wind. Tall slender masts subject to large compression loads are vulnerable to buckling. A failure analysis which can predict large displacements and buckling is required. Analytical formulas exist for simple cross-sections and prismatic members. This is not the case for tapered masts with non-prismatic cross-sections, non-uniform wall thickness, and for prestressed masts that are constructed of tension and compression elements. The use of prestressed tension stays, the presence of prestress, and inherent nonlinearities ─ all contribute to the intricate structural behaviour and stability analysis of masts.

There are a number of papers in the existing literature to understand and predict the stability behavior and strength of stayed masts. Early authors ─ H.R. Mauch (1966), R.J. Smith et al. (1975), Hafez et al. (1979), Hathout et al. (1979), Temple (1977), Temple et al. (1984), and E.A. Smith (1985) produced work of immense value to the profession. More recently, the following researchers and practitioners aming others have contributed to this subject: Van Steirteghem et al. (2003), Saito and Wadee (2009), Samyn (2009), Gurfinkel and Krishnan (2017). A numerical procedure for buckling analysis of compression members under axial loads called the *Stiffness Probe Method* (SPM) was used to calculate the elastic stability of any compression member subject to axial loads (Gurfinkel and Krishnan, 2017). SPM is based on the fact that the local structural stiffness of a compression member degrades from a maximum in the unloaded configuration to zero at the buckling load (Bleich, 1952, Hoff, 1956). It is the use of this measurement and monitoring of stiffness under controlled deformations that allows for an accurate calculation of the critical load. This method proved very effective for the elastic stability analysis of stayed masts.

7. Conclusions

Stayed masts are a sleek, lightweight solution for tall slender compression members. They reduce core size and enhance compression strength by control of prestress. Their efficiency lies in enhancing stiffness through prestress, rather than increasing cross-sectional dimensions. Stayed masts are integral in novel structures like tensioned membranes and stadiums, adding iconic architectural elements. Stayed masts have been given a striking presence in the Astrup Fearnley museum to reminisce the nautical heritage of the country. Hollow elliptical steel sections improve the aesthetic appeal and enhance the structural stability of the masts.

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