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# Slabs with stress-aligned ribs: computational validation of their structural efficiency

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## Abstract

Ribbed slabs are considered to be more structurally efficient than solid slabs (i.e., they achieve equal strength with less material), as proven by the abundant built examples of slabs supported by a grid of straight ribs. A special type of ribbed slabs are slabs with stress-aligned ribs: they were sparsely built in the 20th century, but have regained popularity in academy and industry due to the advent of computational design and digital fabrication, as evidenced in recent experimental projects. While reviewing historical and recent examples of slabs with stress-aligned ribs, this paper shows that, in most scientific literature, their structural efficiency has only been benchmarked against that of solid slabs — a questionable comparison, since any kind of ribbed slabs will achieve a better structural performance than solid slabs. A more relevant approach would be to compare stress-aligned ribs with straight ribs, but few research has been made in this regard. Thus, in order to determine which ribbed slab variant is more efficient, simulations were performed in the Grasshopper environment using Karamba3D, Millipede and SOFiSTiK, modeling the slabs' plates and ribs as steel shell elements. The results proved that slabs with stress-aligned ribs could achieve a significant weight reduction by decreasing their rib thickness and equalizing their internal elastic energy, and consequently, the breakthrough of this research lies in demonstrating the potential of this kind of slabs in terms of material savings.

**Keywords**: Ribbed slabs, Stress-aligned ribs, Isostatic ribs, Principal stress lines, Structural analysis, Computational design

## 1. Introduction

The current trends of computational design, digital fabrication and experimental construction in architecture invite to question the established ways of building; this motivated the author to explore how floor slabs can be improved by taking advantage of these technologies. What would have been achieved by structural architects such as Filippo Brunelleschi, Pier Luigi Nervi or Félix Candela, if they had been able to leverage today's resources? Which innovations they could have brought to slabs? These questions led to developing a master thesis (Ramírez [1]) of which this paper is a summary, stating as its hypothesis that slabs with stress-aligned ribs achieve a higher structural efficiency than slabs with straight ribs.

Validating the structural efficiency of slabs with stress aligned ribs is a relevant endeavor because, although other factors are also considered in real-life applications (e.g., thermal/acoustic insulation, vibration reduction, durability or costs), they can help to reduce the weight and material consumption of floor slabs. This is important since slabs are the heaviest elements of multi-story buildings, making up around 40% of the weight "of a residential reinforced concrete high-rise" (Wolf et al. [2] and Block et al. [3]); thus they represent the main target for decreasing the amount of steel and concrete consumed in the construction industry. Additionally, when the weight of slabs is reduced, the load bearing elements that support them (i.e., columns, beams, walls and foundations) require less material as well.

Most scientific literature focuses on promoting the weight savings of slabs with stress-aligned ribs over solid or flat slabs (e.g., Block et al. [3] or Mata-Falcón et al. [4]). However, to find how advantageous slabs with stress-aligned ribs truly are, a more effective approach would be to compare them to other kinds of ribbed slabs instead. This is the focus of this paper, given that only a few sources mention this benchmark (Moore [5], Ranaudo [6], Prendergast [7] or Reksowardojo et al. [8], for instance).

## 2. State of the art

### 2.1. Explanation of the structural principle

Since forces travel through solids following curved trajectories, slabs can be further optimized if their ribs, instead of being straight, are aligned to these trajectories (see Fig. 1). Theoretically, stress-aligned ribs are considered to have a higher structural efficiency than straight ribs aligned to an orthogonal grid because, when orthogonal ribs receive a load, they will produce torsion to their adjacent ribs due to shear stresses, and thus they must be thick and heavy. Stress-aligned ribs do not transfer loads to each other because shear stresses are absent (Ramírez [9] and Moore [5]). Only principal stresses (pure compression or tension, without shear) act upon each rib, allowing them to be thinner and lighter (see Fig. 2).

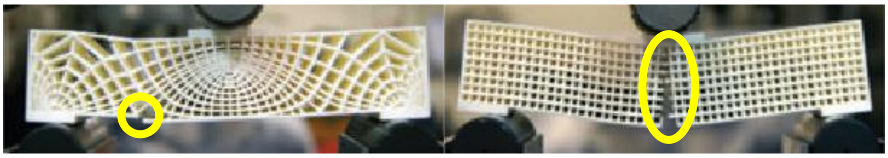


Figure 1: The beam on the left has a stress-aligned internal structure, and is stronger (has a smaller crack) than the one on the right, which has a straight-grid internal structure and is thus weaker (larger crack; experiment by Tam and Mueller [10]). This same structural principle can be applied to optimize ribbed slabs (Ramírez [9]).


Figure 2: From left to right: sketch showing orthogonal ribs causing torsion to each other (Moore [5]); comparison between slabs with thick, orthogonal ribs (PUCMM Library in Dom. Rep., built by F. Camarena in 1975 [11]), and slabs with thin, stress-aligned ribs (Gatti Wool Factory in Italy, built by P. L. Nervi in 1953 [12]); and diagram showing how the ribs of the latter are aligned to the principal stress lines (Halpern et al. [13]).

### 2.2. History of slabs with stress-aligned ribs

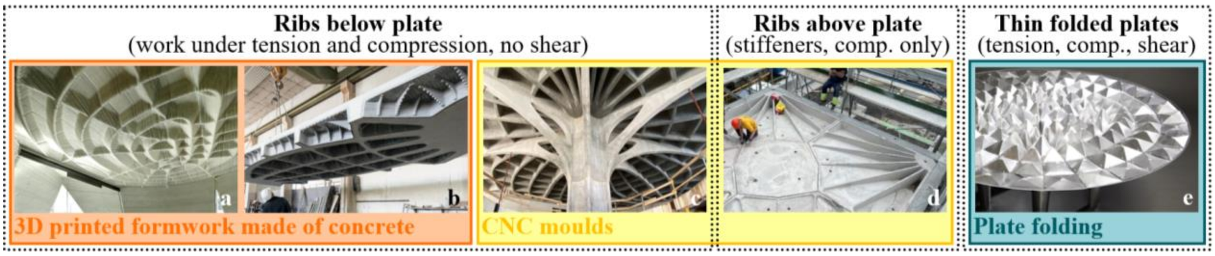
A comprehensive timeline spanning projects from 1949 to 2000 was elaborated, which allowed to discover lesser known examples of slabs with stress-aligned ribs which are not usually mentioned in most literature covering this topic. Fig. 3 shows a selection of these projects, not only including Italian architect and structural engineer Pier Luigi Nervi (who is recognized as the most prolific builder of this structural typology), but also other authors (in particular, it is worth mentioning that the idea of aligning the ribs to the principal stress lines was proposed by Aldo Arcangeli, one of Nervi's employees [13]).

| **Italian patent No. 455678** (Aldo Arcangeli credited as inventor, 1949; [14]) | **Library hall at Bocconi University** in Milan, Italy (Aldo Favini, 1962; [15]) | **Church of the Imm. Heart of Mary** in Bologna, Italy (Pier Luigi Nervi, 1965; [16]) | **Lecture Hall at Freiburg University** in Germany (Hans Dieter Hecker, 1968; [17, 18]) | **High School Gymnasium** in Ueda City, Japan (Gengo Matsui, 1981; [19]) | **"The Constant" architecture book** pub. in Cambridge, USA (Eduardo Catalano, 2000; [20]) |
|---|---|---|---|---|---|

Figure 3: Slabs with stress-aligned ribs designed or built in the 20$^{th}$ century, before the advent of digital fabrication and structural analysis software.

### 2.3. Recent experimental projects

Traditionally, slabs with stress-aligned ribs "had the disadvantage of being more expensive" since "a great variety of moulds is required" and "[their] reinforcement must be curved", which made rebar placement more labor-intensive (Moore [5]). To solve these issues, research on slabs with stress-aligned ribs has gained popularity in the last years (Ramírez [9]). Thus, an extensive Euler diagram was created for the master thesis, classifying recent experimental projects according to which part of the slabs' internal structure is aligned to the principal stresses, their fabrication process and the material they are made of (due to space constraints, a selection of the diagram's most relevant examples is shown below).




a) "3dpod pavilion" by Obayashi in Japan [21]; b) "COEBRO" slab by ITE TU Graz in Austria [22]; c) store by Søren Jensen in Denmark [23]; d) "Rippmann Floor System" by VAULTED AG in Switzerland [24]; and e) "Stress Adapted Folding" project at RWTH Aachen [25].

Figure 4: Recent experimental projects of slabs with a stress-aligned internal structure (extract from Ramírez [1]; the original Euler diagram displays 17 projects, 6 fabrication processes and 5 internal structure categories).

## 3. Methodology

### 3.1. Employed software

The slabs were modeled in Grasshopper (Rhinoceros' visual programming add-on), while Karamba, a Grasshopper plugin that allows to perform structural simulations via the finite element analysis method (Preisinger [26]), was used for obtaining the stress lines patterns that would define the geometry of the slabs with stress-aligned ribs, and for running the structural simulations.

To ensure that Karamba's output was reliable, its stress lines were compared to those of Millipede (another Grasshopper plugin), and its simulation results were validated with SOFiSTiK, a professional structural analysis software. SOFiSTiK was preferred over alternatives such as Abaqus or Ansys because it allowed direct integration via its "Rhinoceros/Grasshopper Interface"; also, the trustworthiness of both tools is proven by them being employed by renowned researchers (such as Bedarf et al. [27] and Kam-Ming [28] for Millipede; or Gil et al. [29] and Huber et al. [30] for SOFiSTiK).

Although Millipede and SOFiSTiK share significant similarities with Karamba (for instance, they also employ the finite element analysis method, and a linear elastic material was assigned for their calculations), several key technical differences justify their use; they are broken down in section 4.1.

### 3.2. Criteria for the structural analysis

The main analysis sequence consisted in comparing the performance of three slab variants, each having a different rib configuration: orthogonal ribs (0°–90°, representing the "voided slabs" that are common in the construction industry); diagonal ribs (45°–135°, to take into account the influence of the grid orientation); and ribs aligned to the principal stress directions (for answering the core research question).

The following slab proportions and support conditions were simulated: one-way elongated slabs (6×2 m), two-way square slabs (5×5 m) with point supports in their corners, and two-way square slabs (5×5 m) with linear supports in their edges. However, since the simulations proved that stress-aligned ribs are not effective for one-way elongated slabs, these are omitted in this paper. Similarly, both pinned and fixed supports were examined, but only the former were considered since most of the existing slabs with stress-aligned ribs show a pinned support behavior, due to ease of construction and calculation.

To simplify the structural analysis and to increase compatibility across the employed software, a "material-neutral" approach was chosen, assigning to the slabs an isotropic and homogenous material without an internal structure (e.g., structural steel instead of timber or reinforced concrete).

Additionally, a uniformly distributed load of 4 kN/m² (which corresponds to live loads in offices; Preisinger [31]) and the slab's self-weight (calculated with Karamba's default value of $g$ = 10 m/s²) were applied. And lastly, the slabs were considered as being made of thin sheet elements, and thus not only their plates were modeled as shells, but also their ribs. The reasoning behind this is that beams in Karamba are discrete, straight elements that cannot follow truly curved trajectories, while shells are continuous elements that can follow the curved path of a rib from start to end; also shells in Karamba are better suited for simulating ribs made of thin materials such as metal sheets.

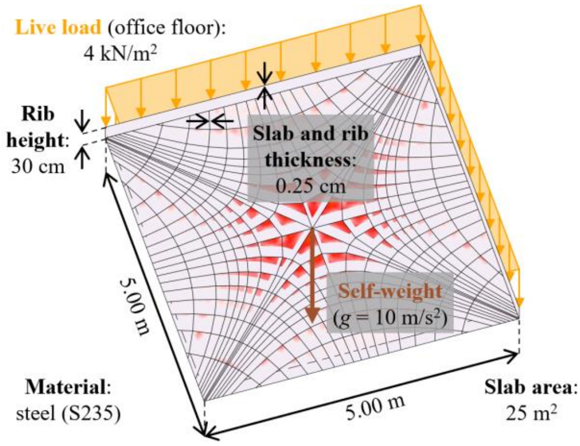



Figure 5: Specifications for the structural simulations (final iteration). Note that, due to the aforementioned criteria, the resulting pattern of the stress-aligned ribs is only optimal for an isotropic, linear elastic material subject to static loads. If these conditions were changed, a different pattern would have been generated.

### 3.3. Generation, spacing and post-processing of the ribs' stress lines and grids

Karamba's most widespread procedure for generating principal stress lines relies on using random source points populating the whole surface of shell elements. Since this leads to the generation of an excessive amount of stress lines, a low number of source points with controlled spacing was employed to govern the separations and positions of the stress lines. These source points were located at straight lines in the slab edges, or in straight lines which crossed through the middle of the slabs (see Fig. 6).

For earlier iterations the spacing of the source points was equal to the rib spacing of the orthogonal and diagonal grid variants, so that the stress-aligned ribs had a separation as similar as possible to the latter. However, it was not possible to obtain a uniform spacing of the stress lines since they become closer and farther from each other by freely following the flow of forces. Thus, this criteria was discarded in a further post-processing step, which consisted in eliminating voids where a lack of ribs caused high stress concentrations. This was made by adding straight ribs crossing through the center of the slab (creating "+" and "×" figures), and by attracting some source points towards this region (see Figs. 6 and 7).

Lastly, after performing several iterations following a trial-and-error strategy, the mesh resolution of the slabs was increased until symmetrical stress lines were obtained, and also polylinear ribs (i.e., ribs that approximate the curved stress lines with straight line segments) were tested (see Fig. 7).

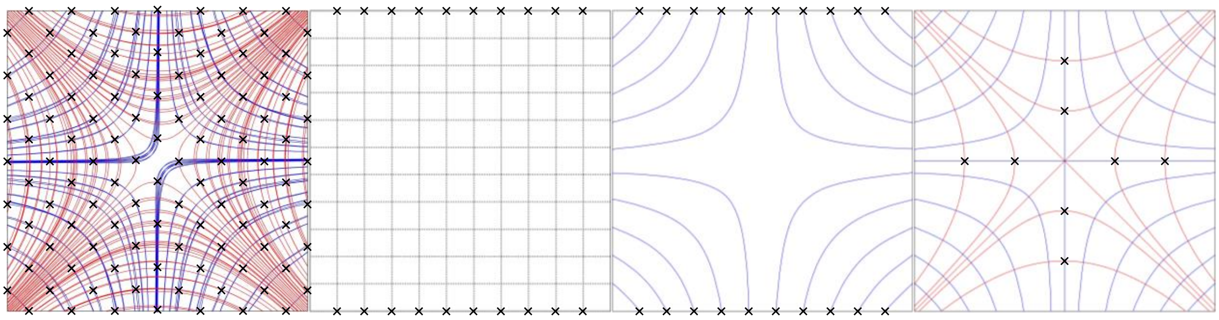


Figure 6: From left to right, excessive stress lines due to source points populating the whole slab; orthogonal grid of ribs; 1st principal stress lines using the same spacing as the orthogonal grid for its source points (early iteration, notice lack of symmetry due to low mesh resolution); and source points for the 2nd principal stress lines with additional lines crossing through the slab center.

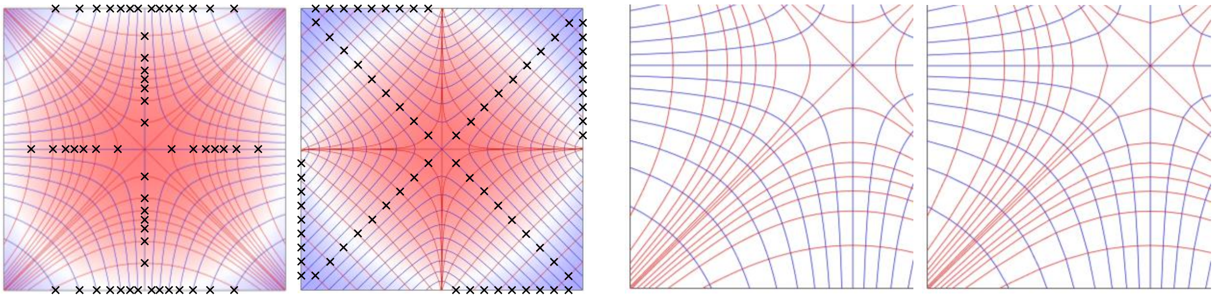


Figure 7: Left pair: stress lines and source points of the final iteration, for slabs with point supports (left) and with linear supports (right); notice the symmetrical stress lines due to a higher mesh resolution. Right pair: differences between curved and polylinear stress lines (easier to see in the top right regions of each image).

### 3.4. Benchmarking and structural optimization

The main parameters used for benchmarking the performance of the slab variants were their mass (kg), internal elastic energy (kN·m) and local maximum displacement (cm), since "the more efficient a structure, the smaller the maximum deflection, the amount of material used and the value of the internal elastic energy" (Preisinger [32]). Internal elastic energy is also known as "strain energy", it was used to determine the structural efficiency of each slab variant, and can be understood as how much energy is stored inside of the slab plates and ribs due to them being tensioned or compressed (i.e., how much an object is stretched or compressed to the point that it will contract or bounce back).

Similarly, internal elastic energy and mass are directly related to one of the easiest ways of optimizing each slab variant: reducing their rib thickness in order to decrease their weight. Thus, rib thickness was chosen as the variable to be modified in a subsequent optimization step, in which the slab variant with the lowest internal elastic energy had its rib thickness reduced until its internal elastic energy was made equal to that of the slab variant with the second lowest energy value. This determined how much the structural efficiency could be translated as weight reduction, and was a valid approach since it is equivalent to the "minimization of strain energy" strategy employed by Tam and Mueller [10].

Adjusting rib thickness allowed to perform a fair benchmark because it preserves the effect of the rib geometry; other parameters (such as increasing the plate thickness or increasing the rib height) reduce the influence of the ribs (i.e., if the slab plate becomes too thick or the ribs become too deep, all the variants will achieve similar performance regardless of their rib pattern, preventing the slab variants from being compared to each other; this is explained more thoroughly in section 4.2).

## 4. Results

### 4.1. Validation with comparative simulations

The stress lines generated in Karamba proved to be correct since similar patterns were obtained with Millipede (see Fig. 8); this becomes more relevant when considering that in Millipede, the positions of loads and supports are input as "boundaries" (regions in 3D space enclosed by a Brep) instead of discrete mesh vertices as done in Karamba; additionally, Millipede (just as SOFiSTiK) employs "quads" instead of triangle faces for the meshes (Steeple [33]), creating an algorithm that is not the same as Karamba's.

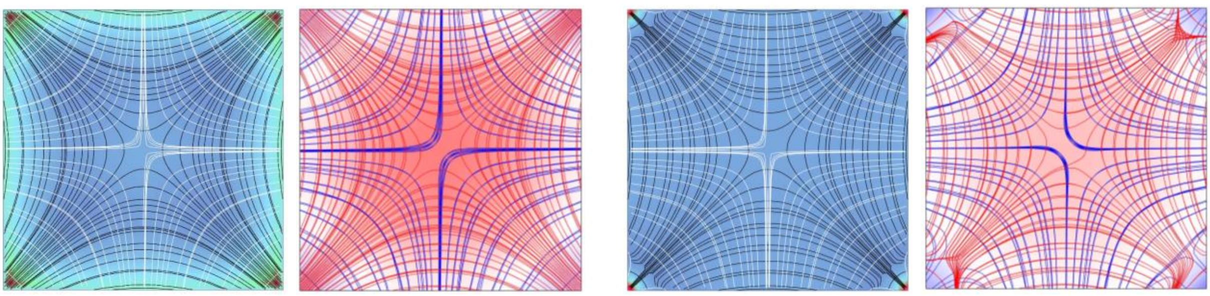


Figure 8: Comparison between the stress lines patterns of two-way, square slabs with point supports in their corners: Millipede-generated patterns (black and white) and Karamba-generated patterns (red and blue); pinned supports in the left pair and fixed supports in the right pair.

On the other hand, the deformed models (see Fig. 9) and numeric values of Karamba's results where validated by comparing them with their SOFiSTiK counterparts, which offered the advantage of being obtained from quad meshes — an approach that can be more precise than Karamba's triangle meshes, since "most structural analysis solvers provide much more accurate results when given a pure quadrilateral (as opposed to triangle or mixed) mesh as input" (Docampo [34]). Also, SOFiSTiK's quad meshes are generated (and joined together) automatically from surface (Brep) inputs, simplifying the meshing process and reducing the probability of any user-induced inaccuracies as can occur in Karamba. Lastly, the displacements obtained in SOFiSTiK were higher than those of Karamba just by a very small margin; this was due to quad meshes being less stiff than triangle meshes (a deeper explanation, based on an analogy of trusses and struts, can be found in Ramírez [1]).

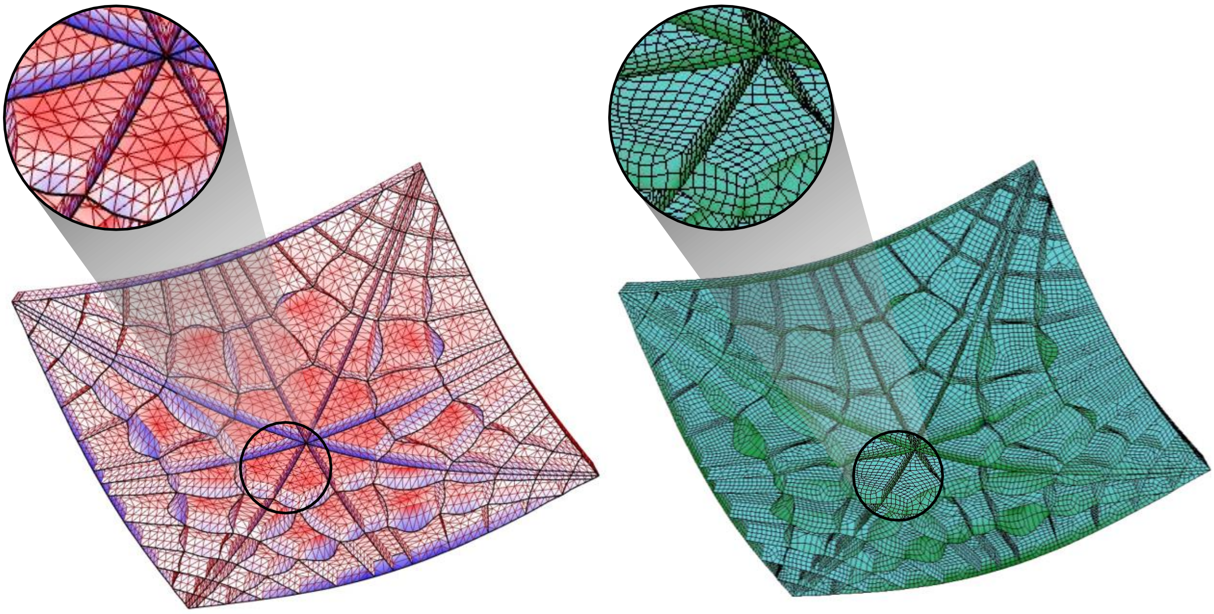


Figure 9: Exaggerated deformation models from Karamba (left) and SOFiSTiK (right). Notice how Karamba uses a triangle mesh while SOFiSTiK uses a quad mesh, that the ribs deformed with the same lateral spreading, and that the bending of the slab plates was identical.

### 4.2. Iteration, evaluation and interpretation

After performing all the structural simulations, it was found out that the greatest weight reduction was achieved in the case of slabs with point supports, while all the slabs had lower displacements when linear supports were applied. A key highlight is that, originally, in the first iterations slabs with stress-aligned ribs always obtained the worst performance, and their ribs had a "flowering" or lateral spreading due to torsion. Only when the stress-aligned ribs were switched from being curved to being polylinear the "flowering" disappeared, and slabs with stress-aligned ribs started showing the best structural performance: they achieved the lowest displacement and the lowest internal elastic energy of all variants, leading to the confirmation of the author's hypothesis (see Figs. 10 and 11).

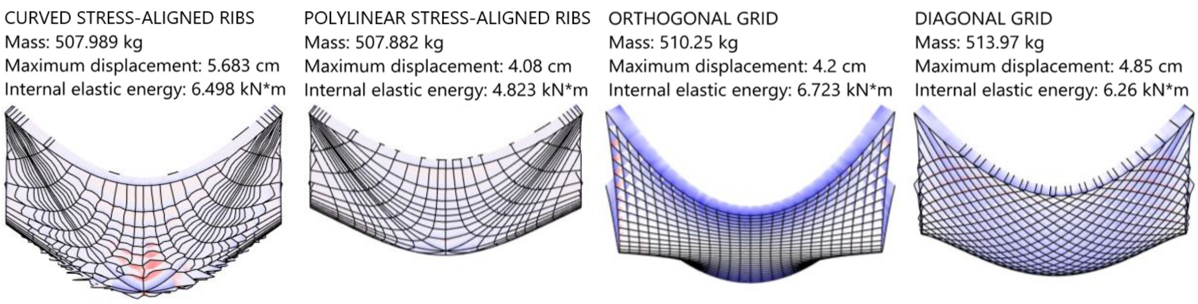



Figure 10: Preliminary results (early iteration), in which, for the first time, slabs with stress-aligned ribs exhibited a significant advantage over the other slab variants by switching from curved to polylinear ribs (notice that the polylinear ribs lack the "flowering" of the curved stress-aligned ribs).

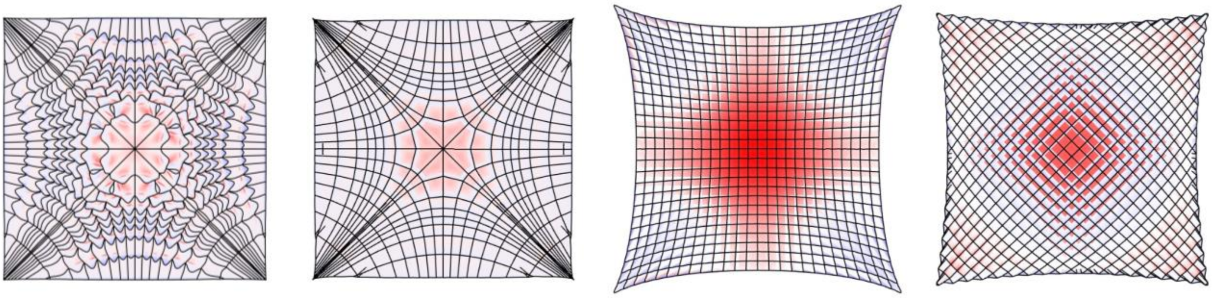


Figure 11: Bottom view of the deformed slabs (from left to right: curved stress-aligned ribs, polylinear stress-aligned ribs, orthogonal ribs and diagonal ribs). The "flowering" of the curved stress-aligned ribs disappeared when they became polylinear, and only the original pattern of the stress-aligned ribs remained the same after deformation, while the ribs of the orthogonal and diagonal variants became warped.

It can be inferred that, for the stress-aligned slab variant, polylinear ribs achieved better results than curved ribs because of two main reasons. First, a curved element that is under tension will straighten before becoming fully tensioned (making it more flexible) while straight elements work more efficiently under tension because they become fully tensioned immediately as they receive a load, making them stiffer. And second, the eccentricity of curved ribs could cause forces at rib intersections to point out of the ribs; polylinear ribs lack this eccentricity, making all forces that originate at the intersections become aligned to the rib trajectories (a more detailed explanation is available in Ramírez [1]).

The influence of rib spacing was not evaluated since this task was more computationally intensive (i.e., it required generating new ribs for each spacing value, while changing the rib height or thickness did not), and also because it was very time consuming (requiring to manually repeat the post-processing of the stress lines). Nevertheless, for the final iteration the orthogonal grid variant had an initial rib spacing equal to 1/25 of its span; a similar fraction (1/20) has been employed by other researchers (Prendergast [7]). This value was chosen in order to obtain a round spacing distance (5 m ÷ 25 = 20 cm) and to produce a relatively high number of ribs, aiming to make the influence of rib geometry easier to detect in the results. This same spacing of 20 cm was also assigned to the ribs of the diagonal variant.

Later, to make the masses of the three variants as equal as possible prior to the benchmark (and thus achieve a fair and unbiased comparison), the rib spacing of the orthogonal variant, which had a lower weight, was reduced to 1/26 of the span (19.23 cm). This increased its rib count by one, leveling its mass without significantly altering its structural performance; doing this was preferred over modifying the rib count of the stress-aligned variant due to the longer time required to generate its rib geometry.

Further simulations were done to determine the influence of rib height and rib thickness as they were changed simultaneously and uniformly across the three variants. Regarding rib height, when it was increased all variants started achieving similar performances; this happened because the structural depth of the ribs diminished the influence of the rib geometry due to their second moment of inertia (i.e., with large rib heights the trajectories followed by the ribs lose relevance, see Fig. 12).

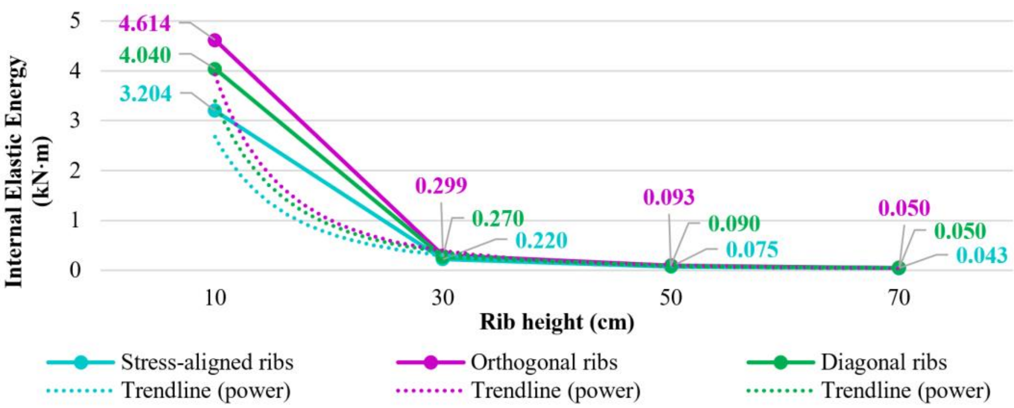



Figure 12: Line chart showing the relationship between rib height, internal elastic energy and the slab variants (point supports). Notice that the lines converge as the rib height increases, meaning that the influence of the rib geometry is inversely proportional to the rib height.

Nevertheless, in the case of rib thickness it was interpreted that the results were not conclusive (see Table 1), since a rib thickness of 0.15 cm produced the lowest internal elastic energy reduction, although by a very small margin. Counterintuitively, higher values were obtained for this parameter by applying thicknesses that were both smaller and larger than 0.15 cm.

Table 1: Influence of rib thickness in the internal elastic energy (IEE) reduction of slabs with polylinear stress-aligned ribs, compared to slabs with an orthogonal grid of ribs.

| Rib thickness (cm) | IEE (stress-aligned ribs; kN·m) | IEE (orthogonal grid; kN·m) | IEE reduction (kN·m) | IEE reduction (%) |
|---|---|---|---|---|
| 0.01 | 3.110 | 4.473 | 1.363 | 30.47 |
| 0.05 | 0.703 | 0.996 | 0.293 | 29.42 |
| 0.10 | 0.399 | 0.561 | 0.162 | 28.88 |
| 0.15 | 0.296 | 0.416 | 0.120 | 28.85 |
| 0.20 | 0.244 | 0.344 | 0.100 | 29.07 |
| 0.25 | 0.213 | 0.301 | 0.088 | 29.24 |

In the end, the structural optimization step described in section 3.4 was carried out. This led to the final iteration, in which it was determined how much weight savings could be achieved by the variant with stress-aligned ribs (which had the lowest internal elastic energy of all variants), by reducing its rib thickness until its internal elastic energy became equal to that of the orthogonal grid variant (which in turn had the second lowest internal elastic energy value). A significant advantage was obtained in the case of point supports, where the stress-aligned variant reached 28% weight reduction (see Fig. 13).

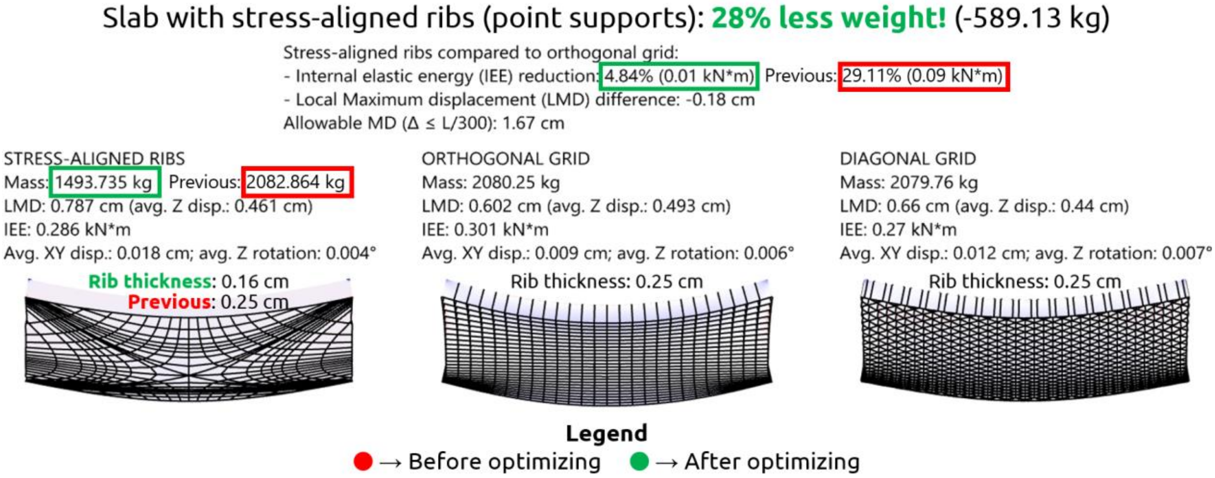



Figure 13: Final iteration results for slabs with point supports, after performing the structural optimization step.

For linear supports the stress-aligned variant offered a lower advantage (16% weight reduction), a moderate result that is explained by two reasons. First, since the entire perimeter of the slabs was supported, less bending was caused; and second, the stress lines pattern of linear supports allowed a larger portion of the ribs in the orthogonal and diagonal variants to be aligned to the principal stress directions, hence the benefit of stress-aligned ribs was not leveraged as much as possible.

## 5. Conclusion

The hypothesis stated in the master thesis was proven: computer simulations demonstrate that slabs with stress-aligned ribs are more structurally efficient than slabs with an orthogonal or diagonal grid of ribs. Further research could focus on applying other structural simulation paradigms (e.g., isogeometric analysis, nonlinear elasticity, anisotropic materials), or performing physical tests to check if the results from the calculations also occur with real prototypes. Especially, it should be found out if polylinear stress-aligned ribs have a superior structural performance than their curved counterparts, since curved stress-aligned ribs could have produced poor results due to the limitations of finite element analysis.

Promising results were obtained in the case of point supports. Because of this, the author proposes to continue this research as a PhD project or as a startup company (see Fig. 14), in an effort to accomplish the reinstatement of slabs with stress-aligned ribs as a relevant solution for the construction industry.


Figure 14: Further research streams. Left: master thesis model representing continuation of the work in academia; right: renderings of slabs with stress-aligned ribs made of diverse materials, symbolizing an innovative industrial venture (the grayscale image is a tribute to Pier Luigi Nervi's Gatti Wool Factory).

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## References

[1] V. Ramírez, "Computational Validation of the Structural Efficiency of Slabs with Stress-Aligned Ribs," Lehrstuhl für Tragkonstruktionen, 2023. Accessed: Feb. 9 2024. [Online]. Available: https://publications.rwth-aachen.de/record/978530?

[2] C. de Wolf, M. Ramage, and J. Ochsendorf, "Low Carbon Vaulted Masonry Structures," *Journal IASS*, vol. 57, no. 4, pp. 275–284, 2016, doi: 10.20898/j.iass.2016.190.854.

[3] P. Block, C. Calvo Barentin, F. Ranaudo, and N. Paulson, "Imposing Challenges, Disruptive Changes: Rethinking the Floor Slab," in *The Materials Book: Inspired by the 6th LafargeHolcim Foundation Forum*, 2019. [Online]. Available: https://www.researchgate.net/publication/338006235_Imposing_Challenges_Disruptive_Changes_Rethinking_the_Floor_Slab

[4] J. Mata-Falcón *et al.*, "Digitally fabricated ribbed concrete floor slabs: a sustainable solution for construction," *RILEM Tech Lett*, vol. 7, pp. 68–78, 2022, doi: 10.21809/rilemtechlett.2022.161.

[5] F. Moore, *Comprensión de las Estructuras en Arquitectura*. Mexico: McGraw-Hill, 2000.

[6] F. Ranaudo, *A low-carbon, funicular concrete floor system: design and engineering of the HiLo floors.* [Online]. Available: https://block.arch.ethz.ch/brg/files/RANAUDO_2021_IABSE_HiLo-floors_1620030416.pdf (accessed: Aug. 17 2023).

[7] S. Prendergast, "Patterns of Optimal Structural Layouts: Patterns of Optimal Structural Layouts," MIT. [Online]. Available: https://dspace.mit.edu/handle/1721.1/139068

[8] A. P. Reksowardojo, G. Senatore, M. Bischoff, and L. Blandini, "Design and Control Benchmark of Rib-Stiffened Concrete Slabs Equipped with an Adaptive Tensioning System," *J. Struct. Eng.*, vol. 150, no. 1, 2024, doi: 10.1061/JSENDH.STENG-12320.

[9] V. Ramírez, *Robotic Fabrication of Slabs with Stress Aligned Ribs*: RWTH Aachen Univ., 2022.

[10] K.-M. M. Tam and C. T. Mueller, "Additive Manufacturing Along Principal Stress Lines," *3D Printing and Additive Manufacturing*, vol. 4, no. 2, pp. 63–81, 2017, doi: 10.1089/3dp.2017.0001.

[11] G. L. Moré, *Historias para la construcción de la arquitectura dominicana.* [Online]. Available: https://issuu.com/centroleon/docs/historias_para_la_construcci_n_de_la_arquitectura_/162

[12] Archinerds, *Gatti wool factory […].* [Online]. Available: https://www.facebook.com/archinerds/photos/a.535058319992194/1069472383217449/?type=3&theater (accessed: Nov. 23 2021).

[13] A.B. Halpern, D.P. Billington, and S. Adriaenssens, *The ribbed floor slab systems of pier luigi nervi*, 2013. [Online]. Available: https://www.researchgate.net/publication/294700249_The_ribbed_floor_slab_systems_of_pier_luigi_nervi
[14] R. Gargiani, A. Bologna, and J. Haydock, *The rhetoric of Pier Luigi Nervi: Concrete and ferrocement forms*. Lausanne: EPFL Press, 2016.
[15] Fondazione Aldo Pio Favini, *Lecture hall of the library of Bocconi University*. [Online]. Available: https://www.fondazionefavini.it/en/opere/lecture-hall-of-the-library-of-bocconi-university/
[16] R. Lampert, *40 éve halt meg Gio Ponti és Pier Luigi Nervi: együtt, de külön is világraszólót alkottak.* [Online]. Available: https://epiteszforum.hu/40-eve-halt-meg-gio-ponti-es-pier-luigi-nervi-egyutt-de-kulon-is-vilagraszolot-alkottak (accessed: Aug. 15 2023).
[17] Universität Freiburg, *Natural Sciences Campus – Campus Tour*. [Online]. Available: https://www.osa.uni-freiburg.de/campustour-en/natural-sciences-campus/ (accessed: Aug. 17 2023).
[18] H.-D. Hecker, *Hörsaal für das Zoologische Institut der Universität Freiburg*. [Online]. Available: http://www.hdhecker-architekt.com/Hoersaal.html (accessed: Aug. 4 2023).
[19] G. Matsui, "On Stream Line Curved Beams: [Memoirs of the School of Science & Engineering. No. 46]," 1982. [Online]. Available: https://gengo-matsui.musalab.co.jp/pdf/paper03.pdf
[20] E. Catalano, *The constant: Dialogues on architecture in black and white*: Cambridge Arch., 2000.
[21] H. Abdel, "3dpod Pavilion / Obayashi," *ArchDaily*, 28 May., 2023. https://www.archdaily.com/1001512/3dpod-pavilion-obayashi (accessed: Aug. 17 2023).
[22] Fakultät für Architektur, TU Graz, *COEBRO Interview - Stefan Peters, Andreas Trummer, Georg Hansemann und Robert Schmid*. [Online]. Available: https://www.tugraz.at/fakultaeten/architektur/aktuelles/fakultaetsnachrichten/interview-2-coebro/ (accessed: Dec. 8 2021).
[23] P. Vejrum, *LinkedIn post*. [Online]. Available: https://www.linkedin.com/posts/peter-vejrum-27996963_til-g%C3%A5rsdagens-festlige-rejsegilde-p%C3%A5-frederiksberggade-activity-7066769577392656384-6Yr6 (accessed: Aug. 17 2023).
[24] P. Finn, "Philippe Block on Sustainable Construction: "Building Technique Is More Important Than Materials"," *Architizer*, 27 Nov., 2023. https://architizer.com/blog/inspiration/industry/philippe-block-on-sustainable-construction-building-technique-is-more-important-than-materials/
[25] J. Musto, M. Lyon, M. Trautz, and L. Kobbelt, "Form finding of stress adapted folding as a lightweight structure under different load cases," in *Form and Force: IASS Symposium 2019*, C. Lázaro and et al., Eds., Barcelona: CIMNE, 2019. Accessed: Jan. 31 2023. [Online]. Available: https://www.ingentaconnect.com/content/iass/piass/2019/00002019/00000013/art00006
[26] C. Preisinger, "Linking Structure and Parametric Geometry," *Archit Design*, vol. 83, no. 2, pp. 110–113, 2013, doi: 10.1002/ad.1564.
[27] P. Bedarf, A. Szabo, M. Zanini, A. Heusi, and B. Dillenburger, "Robotic 3D Printing of Mineral Foam for a Lightweight Composite Concrete Slab," in *Proceedings of the 27th CAADRIA Conference [Volume 2]*, Sydney, Australia, 2022, pp. 61–70.
[28] Kam-Ming Mark Tam, "Stress line generation for structurally performative architectural design," 2016. [Online]. Available: https://www.semanticscholar.org/paper/stress-line-generation-for-structurally-design-Tam/c767cdd5a781ff17d23bc105f163123c1b566a03
[29] M. Gil Pérez, B. Rongen, V. Koslowski, and J. Knippers, "Structural design, optimization and detailing of the BUGA fibre pavilion," *International Journal of Space Structures*, vol. 35, no. 4, pp. 147–159, 2020, doi: 10.1177/0956059920961778.
[30] T. Huber, J. Burger, J. Mata-Falcón, and W. Kaufmann, "Structural design and testing of material optimized ribbed RC slabs with 3D printed formwork," *Structural Concrete*, vol. 24, no. 2, pp. 1932–1955, 2023, doi: 10.1002/suco.202200633.
[31] C. Preisinger, *Loads for typical scenarios*. [Online]. Available: https://manual.karamba3d.com/appendix/a.4-background-information/a.4.3-tips-for-designing-statically-feasible-structures
[32] C. Preisinger, *3.6.1: Analyze*. [Online]. Available: https://manual.karamba3d.com/3-in-depth-component-reference/3.5-algorithms/3.5.1-analyze (accessed: Aug. 13 2023).
[33] N. Steeple, *millipede-backup · GitHub*. [Online]. Available: https://github.com/nickteeple/millipede-backup/blob/master/MillipedeMarch2014.pdf (accessed: Aug. 14 2023).
[34] J. Docampo-Sanchez and R. Haimes, "Towards fully regular quad mesh generation," in *AIAA Scitech 2019 Forum*, San Diego, California, 01072019.