

Structural Design of Post-Tensioned Floors

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The introduction of commercially viable unbonded post-tensioning just over four decades ago added a new dimension to the design and application of concrete floor systems. Longer clear spans, thinner slabs, lighter structures, shorter overall building heights, and the potential for cost savings have made unbonded post-tensioning a prime choice for floor systems.

Post-tensioning in building construction

Unbonded tendons were first used for floor systems in the U.S. in the late 1950s. Their use has increased rapidly since then and there have been considerable developments in engineering and construction techniques. Both consulting engineers and post-tensioning system suppliers have played important roles in the development of the industry. Although extensive application of post-tensioning in building construction is still somewhat new, the initial uncertainties and problems associated with a new technology have been left behind.

Design guidelines and construction practices have matured and are well established within the building industry. These guidelines are given in publications such as the PTI Design Manual (PTI 1990), PTI Technical Notes (Aalami 1993, 1994, 1998, 2000) and ACI-ASCE 423.3R (1996). The guidelines are backed by the

millions of square feet of post-tensioned floor systems in satisfactory service worldwide. Comprehensive information on post-tensioning theory and design is provided in Collins and Mitchell (1991).

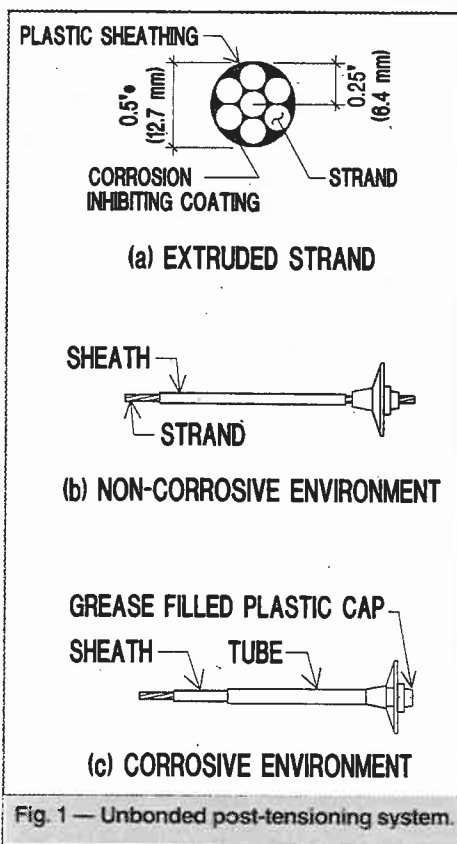
Post-tensioning systems

Post-tensioning is a form of prestressing that uses high-strength steel

strands or bars to apply a compressive stress to concrete. Post-tensioning systems can be either unbonded or bonded (grouted). In the U.S., floors are typically constructed with unbonded systems. Minimum bonded reinforcement is placed in critical locations where cracking may occur.

The tendons consist of 1/2 in., 270 ksi (12 mm, 1860 MPa), seven-wire, low-relaxation steel strands. The strand is greased and encased in an extruded plastic protective sheathing to form a monostrand tendon (Fig. 1). The tendons are laid out at predetermined locations in the forms before the concrete is placed. After the concrete has attained the strength required to support the compressive force, the tendons are stressed and anchored at the slab edges. The cast iron anchorage devices use cone-shaped wedges to clamp the strand (Fig. 2). For added protection in corrosive environments, the wedges and exposed strand tails are covered with a plastic cap (Fig.1(c)). Figure 3 shows an unbonded floor slab.

Figure 4 shows a bonded system. In a typical bonded slab system, two to five strands are encased in a flat metal or plastic duct and anchored with a common anchorage device (Fig. 5). After the tendons are stressed, the duct is filled with a cementitious grout that bonds the strands to the concrete surrounding the duct. Although bonded systems are primarily used in



bridge construction, they are sometimes used for transfer girders and in areas like landscaped plaza decks where heavy loads require a large number of strands. The design procedures are essentially the same for bonded and unbonded systems. There is more loss of prestress due to friction in bonded systems, however, so the final effective force in the strands is slightly lower.

General recommendations governing the sizing and design of post-tensioned systems are given in the *International Building Code* (IBC 2000) and ACI 318 (1999). ACI-ASCE 423.3R (1996) provides specific recommendations for floor systems post-tensioned with unbonded tendons. In addition, the Post-Tensioning Institute has compiled several publications that include design examples and practical construction details (Aalami and Bommer 1999). The PTI Design Manual (PTI 1990) provides information on both post-tensioning systems and post-tensioning design theory; floor slabs are also discussed in a separate publication, *Design of Post-Tensioned Floor Slabs* (PTI 1984).

Post-tensioning design requirements

A conventionally reinforced concrete slab is typically designed for strength (ultimate moment) requirements. Serviceability (crack and deflection control) is addressed by limiting the span-depth ratios and ensuring calcu-



Fig. 4 — Slab reinforced with bonded tendons.

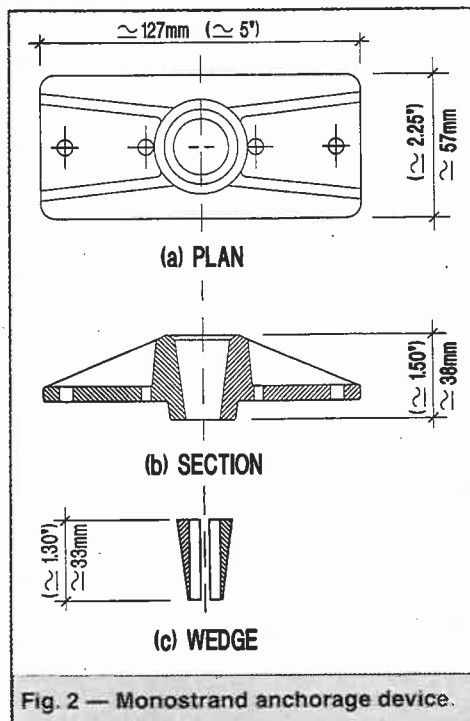


Fig. 2 — Monostrand anchorage device.

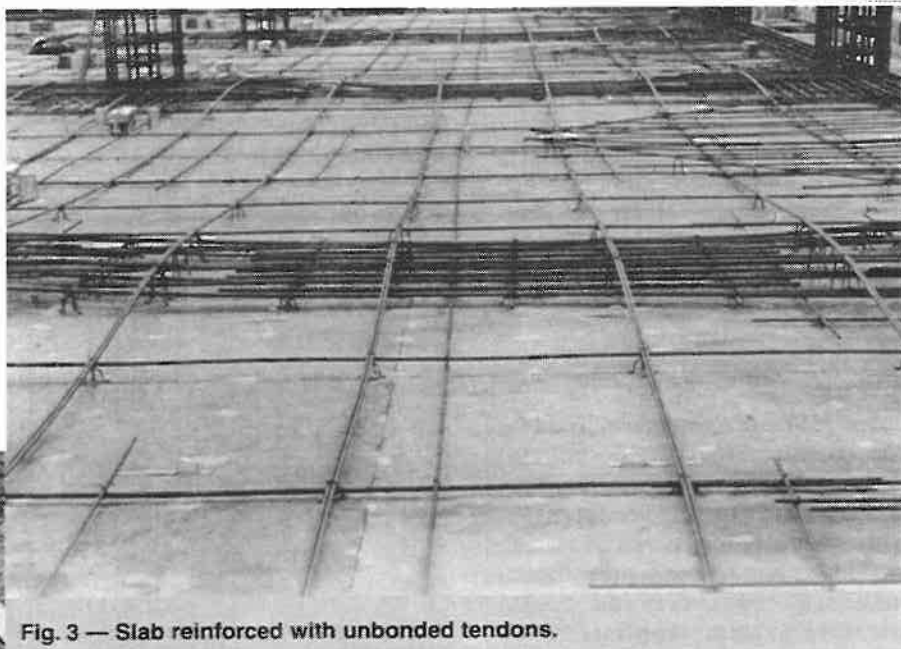


Fig. 3 — Slab reinforced with unbonded tendons.

lated deflections are within acceptable limits. Post-tensioned slabs are designed for both strength and serviceability requirements, however. The post-tensioning is usually designed to satisfy serviceability requirements by limiting stresses under service loading. Nonprestressed reinforcement is added to achieve the strength requirements if necessary. Minimum bonded reinforcement is also required in critical areas where cracking may occur.

Post-tensioning design procedure

Structural modeling

Once the geometry and loading are established, the design of a post-tensioned slab consists of two principal steps, namely, determining the actions (moments and shears) and designing the reinforcement. Design of the post-tensioned reinforcement consists of determining the amount, location, and

profile of the tendons.

The post-tensioned floor-slab systems preferred by the industry are rooted in nonprestressed slab configurations that lend themselves to the application of post-tensioning. The structural modeling of two-way post-tensioned floor systems follows the same guidelines as nonprestressed floors. In brief, the slab is divided into design strips in accordance with designated support lines and load paths. The demand actions (moments and shears) for each design strip are calculated using a frame or finite-element analysis. The design strips are then

checked for reinforcement at selected design sections. Design sections are normal to the support line, and extend over the entire tributary width (the width of the design strip).

Treatment of post-tensioning

When computing moments and shears in a post-tensioned slab, the post-tensioning is typically considered as an applied loading in accordance with the load balancing technique introduced by T. Y.

Lin (1963). The load balancing technique models the effects of post-tensioning tendons as a system of loads acting on the concrete, similar to dead and live loads. This is achieved by considering the tendon removed from its housing (Fig. 6(b) and 6(c)). The effects of the tendon on the concrete are separated into those causing flexure and those causing axial loading (Fig. 6(d) and 6(e)).

The tendon actions causing flexure in the member are referred to as the "balanced loading." The upward force of the tendons on the concrete is considered to offset (balance) a portion of the load on the member, hence the "load balancing" terminology. The stresses that result from the bending are superimposed on those due to the compression caused by the post-tensioning tendons.

The balanced loading diagram must also include the moment that results when the centroid of the member changes. The centroid of a beam or slab will change if its depth changes. The centroid of a slab will also change if there are column capitals or drop panels. Figure 7 illustrates the separation of the post-tensioning actions into those causing flexure and those causing uniform compression. One of the central premises of load balancing is that the solution obtained from the bending of a member can be superimposed with uniform precompression from prestressing. Superposition is only valid if the bending of the member includes the moment shown in Fig. 7(d). This is discussed further in Aalami (1990).

Stress calculations

If a design section is taken at the face-of-support of an elastic

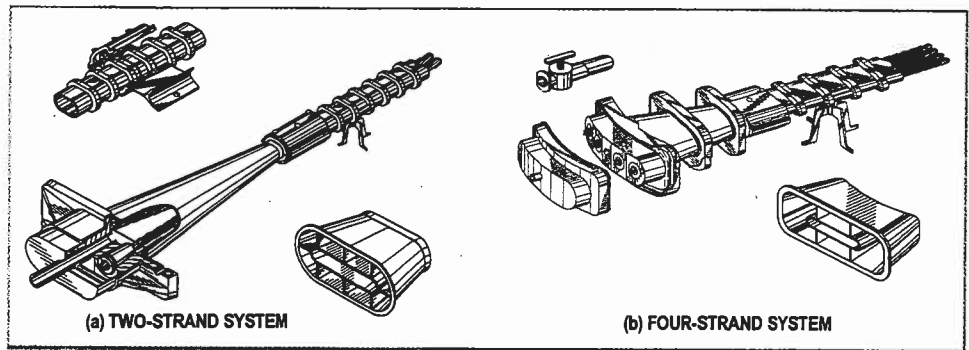


Fig. 5 — Examples of bonded post-tensioning systems (courtesy of GTI-USA).

plate supported on columns, the moment is concentrated at the columns. In post-tensioned slabs, however, ACI 318 recommends that the moment be distributed uniformly over the design section for design. ACI 318 also specifically excludes application of the column-strip/middle-strip concept to post-tensioned floor systems. The moment at each design section is obtained from the analysis of the floor slab. Hypothetical stresses are then calculated by applying the total moment to the entire cross-sectional area of the design section.

These simplified formulas are acceptable for typical member sizing and design. The code-recommended formulas for stress calculation are compatible

with the code-specified permissible stresses and deliver the type of structure intended by the design concept. Figure 8 shows a typical distribution of moment across a design section, along with its idealized stress distribution for checking code compliance.

Load combinations

Control of concrete stresses under service load stresses is required as a serviceability check for post-tensioned members. The objective is to control crack formation under working conditions. For the serviceability check, the moments, shears, and axial loading resulting from the post-tensioning are combined with those resulting from the other loads on the structure. The load

combination consists of the sum of the actions due to dead load, live load, and post-tensioning, combined with a load factor of one. Wind, seismic, and other infrequent transient loads such as impact loading are not considered in serviceability stress checks.

For the strength (ultimate moment) limit state, the section is checked against factored dead and live loads, including infrequent transient loads. The hyperstatic (secondary) moments that result from the post-tensioning are also included. The hyperstatic moments are unfactored.

Design for lateral loading

At this time, there is no simple, widely accepted procedure for modeling post-tensioned slab frames under lateral loading. The Equivalent Frame Method uses the entire slab tributary for gravity loading. The relative column/slab stiffness values for lateral loading are significantly

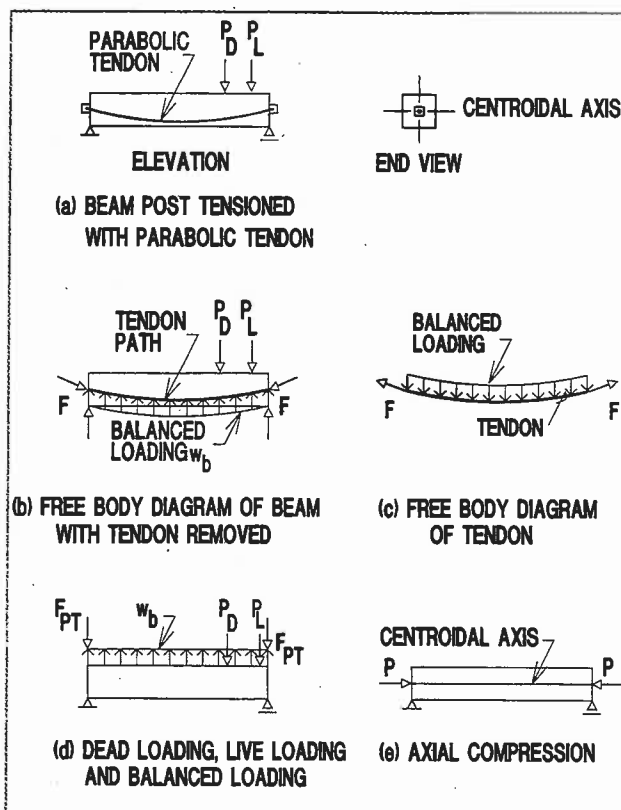


Fig. 6 — Presentation of balanced loading.

different from those used for gravity loading, however. As a result, one-half of the slab tributary is typically used for stiffness computations when determining moments due to lateral loading.

Principal design constraints

The principal design constraints that limit slab and column dimensions of two-way slabs are:

Punching shear

Unless special shear reinforcement is provided, punching shear capacity is the first restriction to the use of long spans in flat-plate systems. A drop cap around the column allows an increase in span length until the punching shear capacity of the slab immediately beyond the drop becomes critical or other limitations are encountered. Drop panels and slab bands can also be used if there is a problem with punching shear. In some situations, however, it may be preferable to keep a flat soffit and increase the slab's punching shear resistance by providing additional reinforcement.

Stirrups and shear heads are sometimes used as punching shear reinforcement in nonprestressed floors. They are not practical for thin post-tensioned slabs, though — it is difficult to anchor the stirrup legs effectively enough for them to develop their full yield strength. Stirrups also interfere with the placement of tendons and nonprestressed reinforcement over supports. Shear heads cannot be used satisfactorily in slabs less than 8 in. (200 mm) deep; this prevents their use in most post-tensioned office and residential slabs.

There are however, a variety of punching shear reinforcement devices which are configured to develop the full tensile strength of their vertical legs in thin slabs. Design of these shear devices is similar to the design of regular stirrups. ACI 421.1R (1992) has recommendations for the design of shear studs. The recommendations can be applied to other shear devices provided they develop their full tensile strength.

Reinforcement congestion

Reinforcement congestion over the columns is an important consideration when using long spans. In unbonded tendon con-

struction, ACI 318 requires a minimum amount of reinforcement over each support for crack control and ductility. This minimum reinforcement is a function of the geometry of the slab and must be placed within a narrow band over the columns.

With long spans, a considerable amount of additional reinforcement may be required to achieve strength demands. Congestion can become a problem because most engineers favor small diameter bars (No. 4 and No. 5 [13 to 16 mm]) for crack control. Small bars are also used to maximize the moment arm of the reinforcing bar and allow more drape for tendons in the perpendicular direction. To achieve effective consolidation of the concrete, the total area of reinforcement over a column should not exceed 6.75 in.² (4200 mm²) in each direction. Drop panels can be used to reduce the amount of reinforcement required.

Deflection

Excessive deflections are very rare in post-tensioned slab systems built in accordance with most current code recommendations; deflections are seldom a limiting criterion. For long-term deflections, a maximum of span/250 can be used as a guideline. When calculating long-term deflections, the gross moment of inertia is used and a creep factor of 2 to 3 is applied to the sustained loading (dead load plus post-tensioning). If a frame analysis such as the equivalent frame method is used, deflections obtained from the strips in both directions must be combined.

Average precompression

ACI 318 requires a minimum average precompression of 125 psi (0.86 MPa). The average precompression (P/A) is the post-tensioning force in the member divided by the cross-sectional area of the member. (In two-way slab systems, the design strip is the member.) For common dimensions and residential/office occupancies, an average precompression between 150 and 250 psi (1.0 and 1.7 MPa) usually produces a satisfactory solution. It is rarely necessary for the precompression to exceed 300 psi (2.0 MPa) in floor slab systems. At

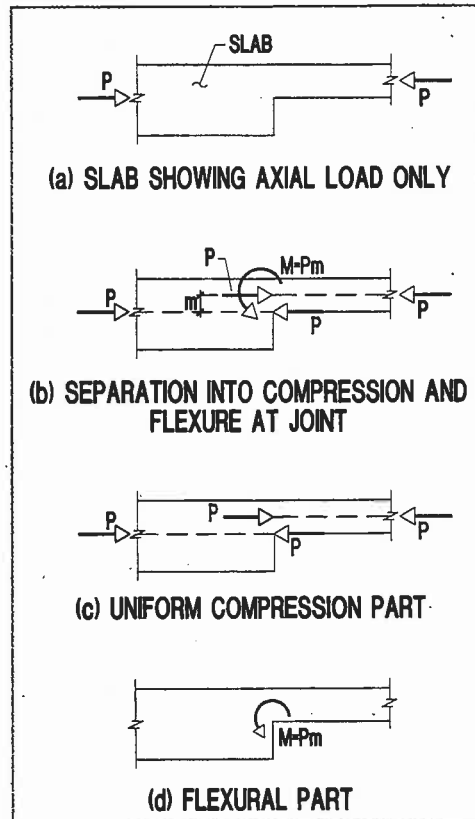


Fig. 7 — Separation of prestressing into flexure and axial components.

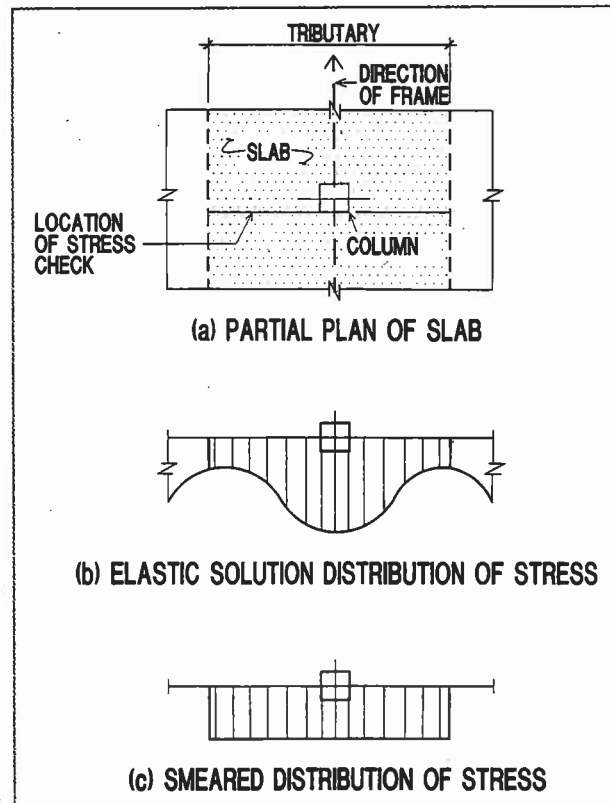


Fig. 8 — Hypothetical stresses for code compliance.

precompression levels above 500 psi (3.4 MPa), restraint from the supports and slab shortening becomes important and needs to be considered. This is particularly true in the lower levels of a building and in buildings with unfavorable support arrangements.

Increasing the depth of a lightly loaded slab may actually increase the required post-tensioning due to minimum precompression requirements. In a typical slab, however, increasing the slab depth will allow an increase in the tendon drape and thus a decrease in the required force.

Construction considerations

Tendon layout

Several schemes were initially proposed for the layout of tendons in two-way floor systems. These included: uniformly distributed in both directions, banded in both directions, and banded in one direction and distributed in the other. Test results concluded that the tendon arrangement is not critical to the slab performance; it is the tendon drape and the total force in the bay that govern slab behavior.

The most commonly used layout is banded in one direction and uniformly distributed in the other. The tendons in the uniform direction are typically spaced approximately 3 ft (1 m) on center. Depending on the required force, the tendons may be bundled in groups of two or three. ACI 318 requires that a minimum of two tendons pass through the column cage in each direction. This helps to ensure the structural integrity of the floor system and prevents progressive collapse in the event of a catastrophic loading.

Nonprestressed reinforcement

As noted above, the codes require a minimum amount of nonprestressed reinforcement for ductility and crack control in unbonded two-way post-tensioned slabs. The reinforcement is not broken down into column strips and middle strips as is typical with nonprestressed slabs, however. Most codes require that the top bars in both directions be concentrated over the supports in post-tensioned slabs. The bottom bars in the banded direction are commonly placed within the width of the banded tendons. The bottom bars in the distributed direction are placed uniformly across the entire bay.

Some engineers use a bottom mat

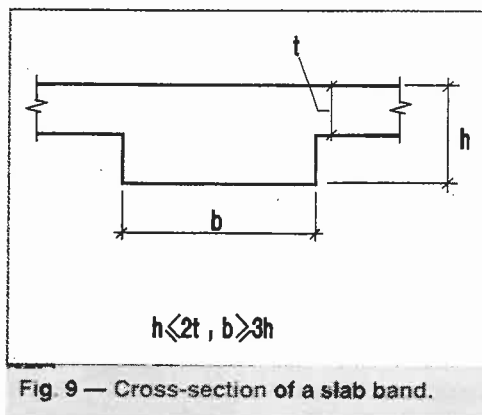


Fig. 9 — Cross-section of a slab band.

of No. 4 at 24 in. or No. 5 at 30 in. (13 mm at 600 mm or 16 mm at 750 mm), both ways, for improved crack control. This typically satisfies the bottom steel requirements and is particularly beneficial in the lower levels of a building where restraint from the foundation walls is likely to reduce the effective prestressing in the floor and lead to cracking.

Special design conditions

Slab bands

When the supports of a uniform floor slab are such that the spans are substantially longer in one direction than the other, the longer span typically governs the slab thickness. In post-tensioned slab construction, the effect of the longer span can be reduced if the tendons in the long direction are banded and placed with an increased drape to provide additional upward forces. This allows the slab thickness to be based on the span length in the short direction.

Slab bands, also referred to as wide, shallow beams (Fig. 9 and 10), are essentially a thickening of the slab along the column lines to allow additional drape. There is no maximum absolute value for the band depth h . In order for the bands not to be considered as supports, however, the two-way action of the floor system must be retained. Localized stiffening of the slab to an extent that would significantly inhibit slab deformation must therefore be avoided. The recommended dimensions are band depth h less than or equal to twice the slab thickness ($h \leq 2t$), and band width b greater than or equal to three times the total band depth ($3h \leq b$).

Concluding remarks

The structural modeling of a post-tensioned floor follows the same general guidelines as a nonprestressed floor. The determination of the location, amount, and profile of post-tensioning tendons is not completely straightforward, however. Depending on the experience and preferences of the design engineer, as well as the design tools (software) used, different designs may result for the same geometry and design parameters. This paper presents the major issues involved in two-way post-tensioned slab design and reviews some of the design criteria that should be adhered to. The intent is to provide engineers with a clear understanding of the principles involved so that the result is a safe, economical design.



Fig. 10 — View of a slab band.

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