FIELD NOTE

New Observations on the Restoration of Notre-Dame in Paris

CAROLINE BRUZELIUS
Duke University

In the months after the fire of 15 April 2019, it did not seem as though anything good could soon emerge from the badly wounded cathedral of Notre-Dame.[1] The broken vaults, with a web of melted and welded scaffolding erected for the restoration of the spire hovering above them, presented a series of formidable challenges. The fire caused severe damage to the mortar and limestone of the surviving vaults, where portions suffered thermal shock from intense heat followed by quick cooling from the water used to douse the flames (Figure 1). The possible destabilization of the equilibrium between the vaults and the flying buttresses posed the threat of further collapse: Did the surviving vaults and upper walls retain enough of their compressive strength to remain in place? Would the greater weight of the vaults—which had absorbed massive amounts of water and were loaded with debris from the incinerated timber frame of the roof—so alter the structure's equilibrium that the flying buttresses might, unopposed by corresponding thrust in the collapsed vaults, exert too much inward pressure, leading to failure? Would the loss of the weight of the roof, and the corresponding removal of vertical compression from the upper walls that "locked" the dynamics of thrust and counterthrust of vaults and flyers into place, further endanger the cathedral's stability?

In the face of this extremely complex situation, President Emmanuel Macron's five-year plan to complete the restoration of Notre-Dame seemed rushed, perhaps even wildly unrealistic. In addition, a layer of toxic dust from the pulverized lead roof and the arrival of the COVID-19 pandemic in early 2020 hampered efforts to carry out timely and effective repairs.[2] And there were still other questions: Where would those leading the restoration find the appropriate stone and wood for the project, as well as the highly skilled workers to prepare these materials? Could the wrecked structure be kept upright and in place when so many factors seemed to conspire against it? How could

Figure 1 Notre-Dame in Paris, detail of the south transept vault, July 2021 (author's photo).

Journal of the Society of Architectural Historians 82, no. 4 (April XXXX), 366–373, ISSN 0037-9808, electronic ISSN 2150-5926.
DOI: https://doi.org/10.1525/jsah.2023.82.4.366.

Figure 2 Notre-Dame in Paris, interior view prior to the fire (cl. 56 P734, Paris MMP).

workers safely remove the melted scaffolding and then stabilize and protect the building, first provisionally and then permanently? The summer after the fire was wet and hot, and the limestone, which absorbs water like a sponge, remained exposed to the elements. In addition to the precarious situation, the discovery of lead pollution led to considerable initial delays.

Yet like the proverbial phoenix rising from the ashes, Notre-Dame is coming back to life. The restoration now rushes toward completion, with the damaged vaults already repaired and new ones replacing those damaged or destroyed by the spire's collapse. Work appears to be on schedule for reopening at the end of 2024. The combined efforts of engineers, architects, restoration experts, masons, carpenters, and *cordistes* (young men who hang like spiders from cranes that soar above the building) are pulling Notre-Dame back together, complemented by the work of a team of expert restorers removing not only pulverized lead dust but also centuries of dirt and soot with latex peels. When Notre-Dame reopens, it will glow more than at any time in modern memory, perhaps even as much as it did when it was first completed in the mid-thirteenth century.

The Organizational Structure of the Research Initiatives

The day after the fire, a prescient group of young French scholars in a wide variety of disciplines organized an international initiative, the Scientifiques au Service de la Restauration de Notre-Dame de Paris, to assert the need for time and access to the building despite the accelerated repair schedule.[3] As stated in a press release, the group's goal was to study the structure and materials of the cathedral utilizing modern analytic methods that would enable the identification of the provenance of the limestone and the dating and structure of the timber, glass, painted surfaces, sculpture, and metal. The research teams adopted state-of-the-art technologies (laser scanning, photogrammetry, dendrochronology, carbon-14 dating, ground-penetrating radar, and metal detection) to delve into questions of dating, structure, construction processes and methods, and chronology. In the long run an interoperable database will make their findings available to the public.

This concentrated multidisciplinary investigation will in time generate more knowledge about Notre-Dame than we have about perhaps any other medieval cathedral, elucidating issues such as the structural dynamics of vaults and flyers, medieval building methods, the dynamics of large-scale construction (such as the character and positioning of scaffolding), and the technology of vault construction. As the first urban megabuilding of its time, Notre-Dame opened the way for the century of Gothic gigantism to follow. Indeed, the cathedral represented a laboratory for the combination of rib vaults and flying buttresses on an enormous scale, a grand experiment in monumental Gothic architectural forms.[4] Notre-Dame as we see it today reflects not only the initial concept as begun ca. 1160 but also, as technology and construction practice rapidly evolved, the enhanced affordances of flying buttresses combined with a thin wall. The cathedral was particularly visible from the moment its walls emerged from the ground, for Paris stood at the crossroads of major road and river arteries that offered splendid views of the site, and the cathedral hierarchy occupied the nexus of the complex political dynamics of the Archdiocese of Sens and the prestigious abbeys of Saint-Denis and Saint-Germain-des-Prés.

Decades ago, I wrote that Notre-Dame was a "building in dialogue with itself," incorporating—or generating—new building technologies and aesthetic preferences in the rapidly changing construction scene of the twelfth and early thirteenth centuries.[5] We can perhaps best perceive the operations of this evolving "design scene" in the decision made in the 1220s—sixty or so years after the creation of the original program, and prior to the completion of the cathedral—to rework the entire clerestory by absorbing the circular openings (oculi) of the middle level (Figure 2). On close inspection, and at both macro and micro levels, change is everywhere present in this cathedral. This brief report focuses on one aspect of these changes: the modification of the chevet design in the nave, a subtle but profound transformation that permitted the highly efficient structure we know today, although, as I will suggest, the structure of the nave may have represented something of a "dead end" in the search for ever greater monumentality in French cathedral architecture.

New Technologies in Research

During the many months in which scaffolding has been present throughout the interior (partially removed as of June 2023), researchers have been provided with periodic access to the upper walls. The intense cleaning necessary to remove lead pollution has also removed centuries of accumulated grime, allowing scholars the opportunity to study and record many previously invisible details. In addition, the use of new and improved technologies to examine the building has generated important new insights. By comparing new scans produced after the fire with scans produced by Andrew Tallon in 2015, engineers have been able to assess possible static shifts in walls and vaults, and carpenters have been aided in their efforts to stabilize the structure, consolidate the flyers, and alleviate pressures against the upper walls.[6] Refined carbon-14 methods have permitted more precise dating of the roof timber, while other new analytic tools have made it possible for specialists to identify the locations of the stone quarries. Last but not least, and at the core of this Field Note, advances in dating methods, along with improved metal detection technologies, have enabled the identification and analysis of the metal used at the cathedral. These investigations have revealed the essential importance of structural metal to the twelfth-century construction process, and the findings suggest that the use of metal technology may have critically influenced the design of the nave itself, as will be explained below.[7]

Eugène-Emmanuel Viollet-le-Duc described and illustrated the use of metal at Notre-Dame in his mid-nineteenth-century *Dictionnaire raisonée de l'architecture française* (Figure 3).[8] However, until recently it remained uncertain whether the metal dated to the initial period of construction (ca. 1160) or to later interventions (Figure 4). Thanks to the work of specialists in historic metals (P. Dillmann, M. L'Héritier, A. Timbert, J.-L. Taupin, and their research teams), we now know that the metal clamps at Notre-Dame mostly date from the medieval period.[9] The bright lights installed for repair work, as well as the scaffolding and cleaning, permitted specialists to identify iron bars and pins in many previously unknown locations; especially important are those for the detached monolithic (*en délit*) shafts of the nave (Figure 5). Ironically, the fire created an opportunity for scholars to conduct what will perhaps be the most thorough and well-documented interdisciplinary study of any cathedral to date, a study that will likely transform important aspects of our understanding of medieval construction.[10]

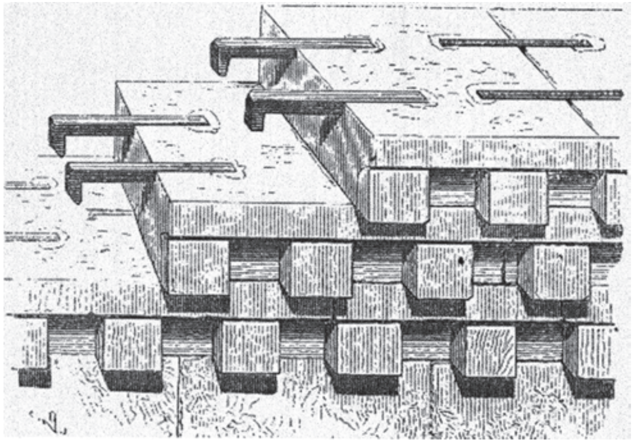

Figure 3 Eugène-Emmanuel Viollet-le-Duc, illustration of iron clamps (Eugène-Emmanuel Viollet-le-Duc, *Dictionnaire raisonée de l'architecture française du XIème au XVIème siècle* [Paris: Bance et Morel, 1854–68], 2:400).

Figure 4 Notre-Dame in Paris, metal bars in the chevet tribune (author's photo).

Metal in Gothic Architecture

Numerous recent studies have addressed the topic of metal in Gothic architecture and the use of metal in antiquity to "lock" masonry blocks together.[11] As emphasized by the metal research team at Notre-Dame, when we look for metal, we often find it. For example, iron dowels are still visible in the unfinished portions of some well-known buildings, for example in the westernmost bay of Chartres Cathedral, where joining pins still project from the engaged shafts awaiting the insertion of separately cut elements (Figure 6).[12]

Figure 5 Notre-Dame in Paris, nave wall from the south tribune toward the north side of the nave (cl. 14072, Paris MPP).

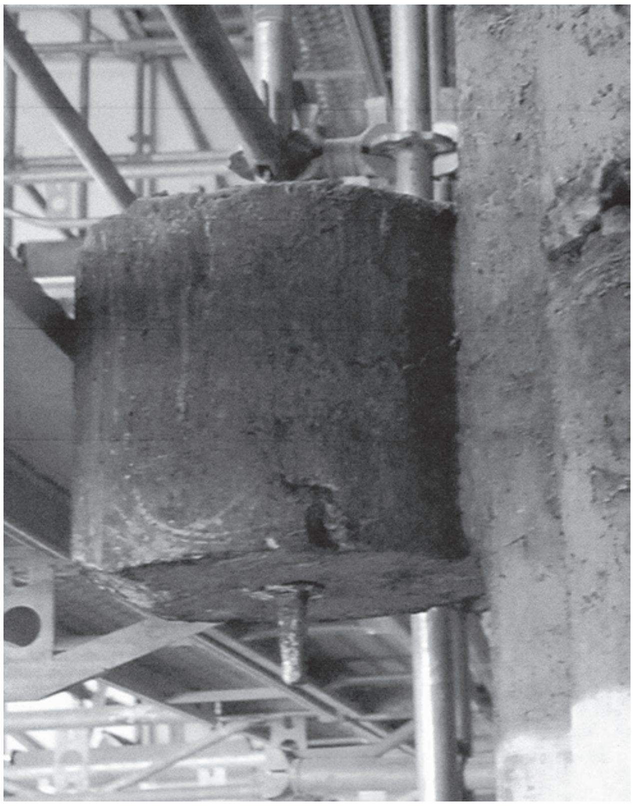

Figure 6 Chartres Cathedral, iron dowels in the westernmost bay of the nave (author's photo).

The earliest iron clamps—shaped like large-scale staples—are visible at Notre-Dame in the tribunes of the chevet of ca. 1170, as Maxime L'Héritier and his colleagues have noted (see Figure 4), and these coincide with several other important design changes: a shift from the large single tribune arches that originally existed in the east wall of the north transept to subdivided openings in the rest of the church (Figures 7 and 8); the adoption of pilasters instead of rounded shafts (Figure 9); and a detached shaft held in place by metal clamps in the southeast corner (Figure 10).[13]

The first pilasters and detached shaft appear on the south side of the chevet tribune and contrast with the handling of forms elsewhere in the east end, representing a pivotal change in design that anticipates key features of the nave elevation.[14] Discreetly introduced in this corner of the chevet tribune, the new forms (pilaster and detached shaft) anticipate the handling of forms not only in the nave aisles, tribune, and main elevation but also the western crossing piers, among the most brilliant achievements of Gothic architecture. Thus, in this corner of the south transept, two central features (pilasters and detached shafts), as well as the new taste for lean, attenuated surfaces, function as a delicate *antipasto* to whet the appetite for the monumental *secondo* of the nave.

On one level, then, the chevet and nave of Notre-Dame are "essays" on the use of limestone in medieval construction: whereas the stones of the chevet are horizontally coursed, respecting their geological formation and taking advantage of their natural compressive strength (see Figure 9), the nave elevation features long, detached (*en délit*) shafts (see Figure 5). These shafts, carved from long slabs of limestone, stand vertically against the nave wall, turned 90 degrees from the sedimentary grain (see Figures 2 and 5). As a result, they are purely decorative, with no structural function. The determination of the builders to develop a thin and attenuated wall surface in the nave drove them in some locations to place the detached shafts against subtle concavities in the wall, as shown in an illustration by Marcel Aubert (Figure 11). Whereas in the chevet the engaged shafts thicken the upper walls of the elevation as a form of internal buttressing, nothing comparable occurs in the nave; here instead the pilasters considerably reduce the mass of masonry, as demonstrated in Aubert's illustration. In this early

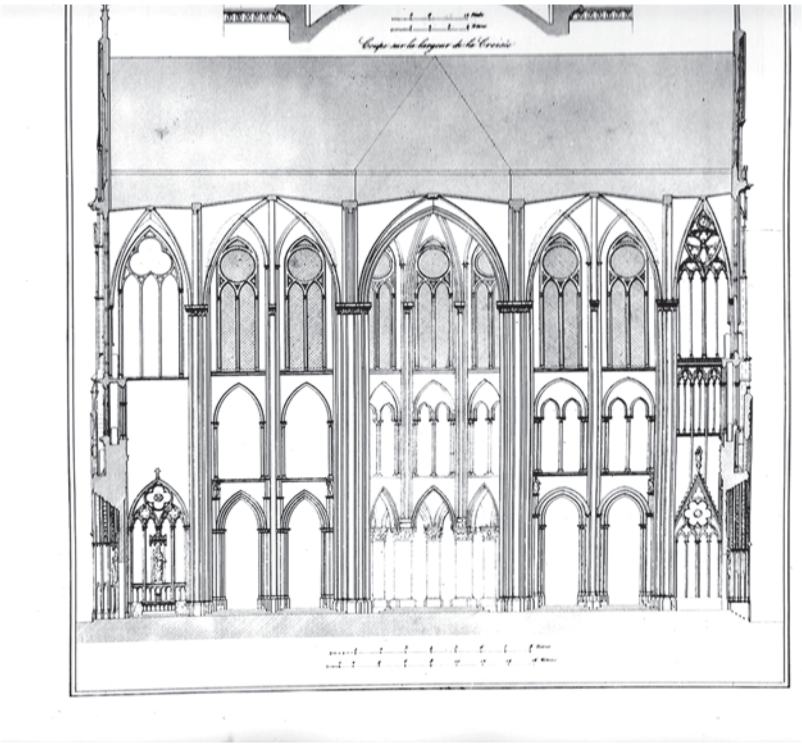

Figure 7 Émile Leconte, view of Notre-Dame in Paris, transverse section of the east transept elevation, 1843 (Émile Leconte, *Notre-Dame de Paris, dessins* [Paris, 1843], reproduced in Alain Erlande-Brandenburg, *Notre-Dame de Paris* [Paris: La Martinière, 1991], 246).

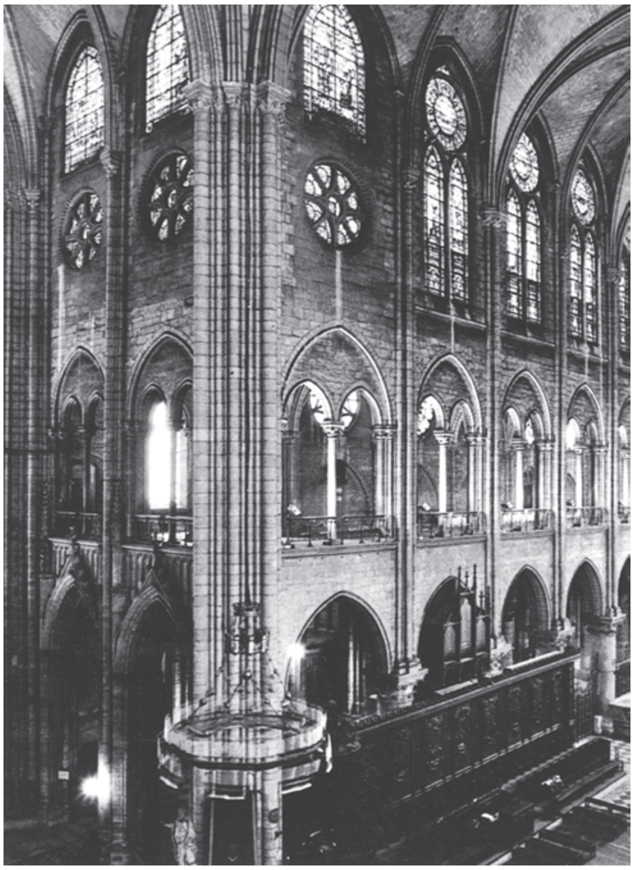

Figure 8 Notre-Dame in Paris, east wall of the north transept and the chevet (author's photo).

Figure 9 Notre-Dame in Paris, pilaster in the southeast corner of the south transept arm (author's photo).

Figure 10 Notre-Dame in Paris, detached shaft in the southeast corner of the south transept arm (author's photo).

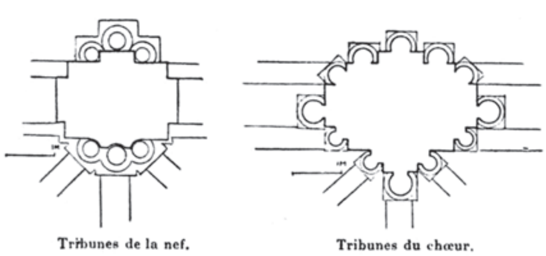

Figure 11 Sections of the responds at tribune level in the nave (left) and the chevet (right) of Notre-Dame in Paris, after an illustration by Marcel Aubert, 1920 (Marcel Aubert, *Notre-Dame de Paris: Sa place dans l'histoire de l'architecture du XII^{e} au XIV^{e} siècle* [Paris, 1920], 42, fig. 2).

moment of Gothic, and thanks to the integration of iron, the nave of Notre-Dame is nothing short of radical: bigger, but also lighter and thinner, in strong contrast to the chevet.[15]

The Aesthetic Implications of the Metal Clamps at Notre-Dame

The distinctly "Parisian look" of the nave of Notre-Dame that sets the cathedral (and its local imitators) apart from

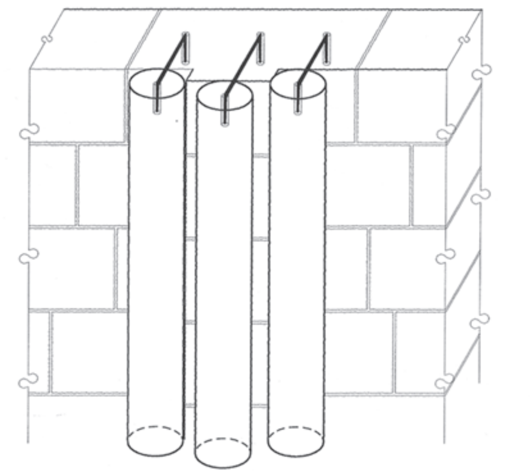

Figure 12 Diagram of the iron clamps holding detached shafts in place in the nave of Notre-Dame in Paris; the probable vertical metal dowels are not shown (diagram by Vickery Cleaves).

later large-scale Gothic buildings is especially striking in the nave, for the most part erected in the last third of the twelfth century, where detached shafts that rise uninterrupted to the departure of the vaults serve as the only bay divisions. In contrast with the structural function of the chevet responds, the nave shafts are a purely aesthetic device. They respond visually (but not structurally) to the transverse and diagonal ribs. Whereas the chevet is monumental, hefty, and muscular, the nave exalts in a thin membrane that nonetheless rises 2 meters higher than the chevet.

As L'Héritier, Dillman, and their teams have demonstrated, a horizontal iron clamp holds each shaft in place, binding its center to the corresponding level of coursed masonry in the wall (Figure 12). The builders coordinated the lengths of the shafts with the horizontal coursing of the wall, so that as the wall reached a certain height, shafts of corresponding length could be lifted into position and attached by metal clamps to the wall behind. Melted lead was poured into the cavities to secure the stones in place, and often the builders seem to have installed lead pads, as well as metal dowels, between the shafts.[16] Following the setting of each level of shafts on a given stretch of wall, construction continued to the point where the next layer of shafts could be positioned and attached. The profound change in approach to structure and wall surface that distinguished the earlier chevet from the subsequent work on the nave derived from the use of iron clamps.[17]

I have described a fluid construction environment. Yet although the nave almost certainly signals the work of a new master mason, we have no documents on the organization of labor or the running of the building works of any cathedral of the twelfth century. Even the date for inception of construction at Notre-Dame, which would have begun with the arduous task of digging the deep foundations, remains uncertain.

The process of fluid and serendipitous change that is so marked in the fabric of the cathedral may also have existed in the emerging development of its administration. Perhaps the scale of the Parisian enterprise (along with the ongoing construction at Sens and other early Gothic sites) was a force in generating, and eventually concretizing, new types of administrative structures for approving the design (such as a geometry to govern proportions), "translating" the initial concept to actual execution, and guaranteeing long-term financing and what we would now call the "supply chain" of materials.[18] There may be a hint about the direction of the ongoing development of the organizational structures of labor and building administration in the fact that in 1164 a mason, Ricardus *cementarius* (mason), had sufficient status to act as a witness of a document regarding a tithe at Champeaux.[19] Might *cementarius* suggest an early description of the master mason, *maître d'oeuvre* or *appareilleur*, as distinct from the higher-level *concepteur* or *architecte de conception*? In any event, at Notre-Dame, given the scale of the building, it seems clear that more than one master mason was at work at a time. I suggested this in 1987 for construction of the nave, and recently Stephan Albrecht and his team have proposed a similar system for the erection of the mid-thirteenth-century transept façades.[20] As long as the builders adhered to certain broad requirements of the overall design, they had considerable latitude in the execution of its individual parts.

Notre-Dame as a Moment in Time

If Notre-Dame has returned as a phoenix after the fire, it may also represent the swan song for a certain concept of wall structure. The flaw lay exactly in the spectacular aesthetic and approach to materials that determined the design of the nave, which later builders in the Gothic style could not expand—or scale up—for the next generation of cathedrals.

As scholars of metal used in medieval buildings have observed, we should no longer consider French Gothic cathedrals as structures made only of the (ostentatiously) visible materials of stone and mortar but rather as the products of a dynamic of stone, mortar, and (mostly hidden) metal. This rethinking has profound structural implications. In the nave of Notre-Dame, from the crossing to the westernmost bay adjacent to the façade, the thickness of the wall was everywhere reduced and the shafts no longer performed a structural function. This reduction of wall mass had vital economic implications: less stone quarried, transported, shaped, lifted, and mortared into place. As Aubert's illustration demonstrates, the redesigned layers of the masonry responds were also easier to carve and less likely to be damaged during installation. The nave of Notre-Dame, pinned between the greater weight and mass of chevet to the east and the façade to the west, represents an efficient and elegant reinterpretation of the original elevation: theme (chevet) and variation (nave).

Perhaps it took the fire at Notre-Dame and the application of state-of-the-art technologies by new interdisciplinary research teams for us to fully appreciate the importance that metal had acquired at building sites by the second half of the twelfth century, and specifically to understand the structural implications of metal for Notre-Dame.[21] The use of metal enabled an exponential leap in scale and a radical slimming down of the masonry walls, with the detached shafts performing "visual pyrotechnics" to suggest weight-bearing structural continuity where none in fact exists.

However, subsequent cathedral designs exposed the limitations of the long, detached shafts in this tour de force of Notre-Dame's nave: long stretches of detached shafts could not be scaled up to meet the demand for increased dimensions and structural heft.[22] The leap of scale in the cathedrals of Soissons, Chartres, and Bourges in the next generation, expanded still further at Reims and Amiens, required all architectural parts to play a significant structural role. In this next phase of ever more ambitious Gothic architecture, the long stretches of fragile detached shafts that characterize the nave of Notre-Dame would have no place.

Keywords: Gothic architecture; medieval construction; iron clamps; metal; Notre-Dame Cathedral

Notes

1. I thank Yves Gallet for many useful and informative conversations, as well as Maxime L'Héritier for answering many questions.

2. For a useful summary of the challenges after the fire, see Yves Gallet, "Après l'incendie: Notre-Dame de Paris; Bilan, réfléxions, perspectives," *Bulletin monumental* 177, no. 3 (2019), 211–18.

3. See the organization's website at https://www.scientifiquesnotre-dame.org (accessed 3 Aug. 2023).

4. The vaults of Notre-Dame are 31 meters high in the choir and 33 meters high in the nave, while the nave walls are only 80 centimeters thick. Given the scale of this building, we can imagine that the program as established by the bishop and chapter was intended to affirm the importance of this cathedral as *mater et caput* of the diocese, as well as the position of Paris as the emerging capital of France.

5. Caroline Bruzelius, "The Construction of Notre-Dame in Paris," *Art Bulletin* 69, no. 4 (1987), 540–69.

6. See Andrew J. Tallon, "Archéologie spatiale: Le bâtiment gothique relevé (et révélé) par laser," in *Architecture et sculpture gothiques: Renouvellement des méthodes et des regards (Actes du IIème colloque international de Noyon, 19–20 juin 2009)*, ed. Stéphanie Diane Daussy and Arnaud Timbert (Rennes: Presses Universitaires de Rennes, 2012), 65–77;

Dany Sandron and Andrew Tallon, *Notre Dame Cathedral: Nine Centuries of History*, trans. Lindsay Cook (University Park: Pennsylvania State University Press, 2021); Andrew Tallon, "Rethinking Medieval Structure," in *New Approaches to Medieval Architecture*, ed. Robert Bork, William W. Clark, and Abby McGehee (Burlington, Vt.: Ashgate, 2011), 209–17.

7. Maxime L'Héritier, "Iron and Lead in Notre-Dame de Paris: An Interdisciplinary Perspective," *Journal of Cultural Heritage*, online 28 Sept. 2022, doi:10.1016/j.culher.2022.09.003. A more recent and very important publication is Maxime L'Héritier, "Notre-Dame de Paris: The First Iron Lady? Archaeometallurgical Study and Dating of the Parisian Cathedral Iron Reinforcements," *PLOS ONE* 18, no. 3 (Mar. 2023), 1–34.

8. Eugène-Emmanuel Viollet-le-Duc, *Dictionnaire raisonée de l'architecture française du XIème au XVIème siècle* (Paris: Bance et Morel, 1854–68), 2:391–400. In 1991, Alain Erlande-Brandenburg briefly mentioned the topic of metal clamps in his *Notre-Dame de Paris* (Paris: La Martinière, 1991), 89.

9. Maxime L'Héritier, Philippe Dillmann, Arnaud Timbert, and Philippe Bernardi, "The Role of Iron Armatures in Gothic Constructions: Reinforcement, Consolidation or Commissioner's Choice," in *Nuts and Bolts of Construction History: Culture, Technology and Society*, ed. Robert Carvais, André Guillerme, Valérie Nègre, and Joël Sakarovitch (Paris: Picard, 2012), 1–8. See also, more generally, Arnaud Timbert, ed., *L'homme et la matière: L'emploi du plomb et du fer dans l'architecture gothique* (Paris: Picard, 2009), esp. 52–118.

10. It is unfortunate, however, that the accelerated schedule of the restoration has not permitted archaeological investigation beyond the rushed and superficial excavation of the crossing: the history of the cathedral, as well as that of Paris, lies underneath.

11. See Lynne Lancaster, ~~Concrete Vaulted Construction in Imperial Rome: Innovations in Context~~ (Cambridge: Cambridge University Press, 2005), 113–27.

12. See L'Héritier et al., "Role of Iron Armatures," 3–4.

13. The single tribune arches resemble those of the tribunes of Senlis. The anomalous tribune openings in the east wall of the north transept were "rectified" by Viollet-le-Duc. On this and the construction chronology of the chevet, see Bruzelius, "Construction of Notre-Dame in Paris," 553–55.

14. This was first observed by William W. Clark and Robert Mark in "The First Flying Buttresses: A New Reconstruction of the Nave of Notre-Dame de Paris," *Art Bulletin* 66, no. 1 (1984), 52n15; as well as by Dieter Kimpel and Robert Suckale in *Die Gotische Architektur in Frankreich 1130–1270* (Munich: Hirmer, 1985), 152–53. Kimpel and Suckale emphasize the originality of the master of the nave design. See also Erlande-Brandenburg, *Notre-Dame de Paris*, 80–90; Bruzelius, "Construction of Notre-Dame in Paris," 549–51.

15. L'Héritier has stated that Notre-Dame "is indisputably the first Gothic cathedral where iron was thought of as a real building material to create a new form of architecture." Quoted in "Notre-Dame de Paris Cathedral ~~Was Historical First in Using Iron Reinforcements~~ in the 12th Century," *Science Daily*, 15 Mar. 2023, https://www.sciencedaily.com/releases/2023/03/230315143833.htm (accessed 3 Aug. 2023).

16. On the lead pads and dowels, see Jenny Alexander, "Solid as a Rock: Poured Lead Joints in Medieval Masonry," in *De re metallica: The Uses of Metal in the Middle Ages*, ed. Robert Bork with Scott Montgomery, Carol Neuman de Vegvar, Ellen Shortell, and Steven A. Walton (Burlington, Vt.: Ashgate, 2005), 255–63, esp. 258–60.

17. In the westernmost bay, the structure is considerably thickened in order to stabilize the great mass of the west façade; see Bruzelius, "Construction of Notre-Dame in Paris," 561–64. On the thickness of the vaults, see Yves Gallet, C. Camerlynck and H. de Lambilly, "L'epaisseur des voûtes dans les cathédrales gothiques," *Bulletin monumental* 180, no. 4 (2022), 344–48, esp. 345. These authors have determined that in the chevet of Notre-Dame the vaults range from 12 centimeters at the keystone to approximately 15 centimeters at the departure, and in the nave from 19 centimeters at the keystone to approximately 24 centimeters at the departures.

18. The terminology is best understood in French, and that is the language adopted here; for important contributions on our understanding of design versus execution and the related terminology, see Jacques Moulin, "Conception architecturale et construction au XIII^{e} siècle: L'église du prieuré Saint-Victor de Bray (Oise)," *Bulletin monumental* 179, no. 2 (2021), 125–54; Dieter Kimpel, "Le développement de la taille en serie dans l'architecture médiévale et son rôle ~~in~~ l'histoire économique," *Bulletin monumental* 135, no. 3 (1977), 195–222; Stefaan Van Liefferinge, "The Hemicycle of Notre-Dame of Paris: Gothic Design and Geometrical Knowledge in the Twelfth Century," *JSAH* 69, no. 4 (Dec. 2010), 490–507; Dany Sandron, *Notre-Dame de Paris: Histoire et archéologie d'une cathédrale (XII^{e}–XIV^{e} siècle)* (Paris: CNRS Éditions, 2021), 57–60.

19. Moulin, "Conception architecturale," 125–54; Benjamin Guérard, *Cartulaire de l'église Notre-Dame de Paris*, 4 vols. (Paris, 1850), 1:71.

20. Bruzelius, "Construction of Notre-Dame in Paris," 562–64; Stephan Albrecht, Stephan Breitling, and Rainer Dewello, *Les portails du transept de la cathédrale Notre-Dame de Paris: Architecture, sculpture, polychromie* (Petersberg: Michael Imhof Verlag, 2022), 64–77, esp. 75.

21. As Jean-Louis Taupin remarks in regard to Beauvais Cathedral, "Metal . . . was the sine qua non, for both the construction and the conception of the great monuments of the era." J.-L. Taupin, "Le fer des cathedrals," *Monumental* 13 (1996), 27, my translation.

22. L'Héritier et al. note the progressive disappearance of detached shafts in the second half of the thirteenth century, and they were on their way out well before. L'Héritier et al., "Role of Iron Armatures," 3.