

Chapter 15

Rethinking Medieval Structure

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In 1963 Robert Branner wrote with characteristic authority that the stability of the upper walls and vaults of the cathedral of Sens was assured not by the flying buttress, which he believed had not yet been invented, but rather by means of 'great quantities of stone'.¹ Kenneth Severens followed suit soon thereafter; he affirmed that the primary piers at Sens, which were three meters deep in section, were large enough to have served as internal buttresses for the flyer-less vaults, whose lateral webs were in any case originally cambered downwards over relatively small clerestory windows, and may thus have required less bracing.² In the mid-thirteenth century, the lateral webs were rebuilt to accept larger clerestory windows; it was at this point, according to Branner and Severens, that the equilibrium of the upper building was disturbed and the installation of flying buttresses became necessary.

In 1982 Jacques Henriët turned the widely accepted story on its ear.³ He was convinced – and rightly so – that flying buttresses had been installed at Sens during one of the early campaigns of construction in the mid-twelfth century.⁴ The archaeology and documentary evidence, though equivocal, generally supported his inference; but he apparently felt as if this were not enough, and resorted to arguments of a purely structural nature, as had Branner and Severens.⁵ For Henriët, however, the upper stories at Sens were weak – far too frail to have been able to withstand the thrust of the vaults without the assistance of flyers. He made no mention of the buttressing potentially afforded by the massive piers,

¹ Robert Branner, 'Gothic Architecture 1160–1180 and its Romanesque Sources', in *Romanesque and Gothic Art: Studies in Western Art, Acts of the Twentieth International Congress of the History of Art* (1961) (Princeton, 1963), pp. 92–3.

² Kenneth Severens, 'The Cathedral of Sens and its Influence on the Twelfth Century' (Ph.D. thesis, Johns Hopkins University, 1968), pp. 59–60.

³ Jacques Henriët, 'La cathédrale de Sens: le parti du premier maître et les campagnes du XIIe siècle', *Bulletin Monumental*, 140 (1982): 81–174.

⁴ *Ibid.*, p. 82; see also Andrew J. Tallon, 'Experiments in Early Gothic Structure: The Flying Buttress' (Ph.D. thesis, Columbia University, 2007), pp. 102–5.

⁵ Henriët, 'La cathédrale de Sens', pp. 137, 140.

nor did he allow that a clerestory wall of considerable height, loaded by the roof, might act to stabilize the entire structural system.⁶

When considered in terms of its structural historiography, then, Sens Cathedral was an eminently sturdy building with substantial internal buttresses and with flyers added in the thirteenth century; in Henriët's hands, in the short space of a decade, it became weak and structurally needy, entirely dependent on flyers placed from the start of construction in the twelfth century.

It is in an attempt to avoid such incongruities that I have begun to seek new ways of letting buildings speak their structural stories more directly through a paradigm that I call *spatial archaeology*, the close observation of building deformation. Spatial archaeology is based on the premise that a building is constructed in plumb; if it is no longer so, we can assume that it was thrust out of true – primarily during the first few years after the completion of construction when mortar was still in a plastic state – by the combined forces of gravity, wind pressure, and temperature variation.⁷ This deformation can be documented with near-perfect precision using a computer-controlled laser, which measures the distance between itself and every surface that it can 'see' at up to 50,000 times

⁶ An unpublished series of finite element and photoelastic tests carried out by Robert Mark, William Clark, and Leonard van Gulick at Princeton University in 1987 suggests that the flying buttresses in fact play a negligible role in the stability of the upper walls at Sens. Two conclusions can be drawn: first, Henriët's rather strident structural arguments must be taken with a grain of salt; and second, the builders of Sens appear to have been concerned for the stability of their unusually wide, vaulted building and overbuilt as a result – a fear-based response that was quite probably responsible for the innovation of what would become a key element of the Gothic toolkit. I am grateful to the authors for allowing me to make use of their analysis.

⁷ 'Medieval masonry in its youth,' wrote Pol Abraham, 'is a soft wax in which are imprinted, recorded for the future, the successive efforts resulting from the slow progress of the building' – 'Viollet-le-Duc et le rationalisme médiéval,' *Bulletin Monumental*, 93 (1934): 83. Abraham's perceptive observations were confirmed two decades later by tests made by French restoration architect Jean-Pierre Paquet, who was responsible for post-Second World War repairs at the cathedrals of Beauvais, Noyon, and the abbey church of Saint-Leu-d'Esserent. 'It is certain,' wrote Paquet, 'that lime mortars remained in a plastic state for several months and sometimes even several years after their initial use. They hardened slowly, and, for a certain time after the centring was removed, deformations took place; later, temporary displacements due to shifting loads and other incidents sustained over the centuries accentuated this evolution' – 'Structures des monuments anciens et leur consolidation,' *Monuments Historiques de la France*, 1 (1957): 168–9. See also John Fitchen, *The Construction of Gothic Cathedrals: A Study of Medieval Vault Erection* (Oxford, 1961), pp. 262–5; and Robert Mark, *Experiments in Gothic Structure* (Cambridge, MA, 1982), pp. 18–19. Note that deformations produced when loads are incurred at early stages in the building process are sometimes rectified during construction, as Rowland Mainstone has demonstrated in his analysis of the construction of the Hagia Sophia. See idem, *Hagia Sophia: Architecture, Structure, and Liturgy of Justinian's Great Church* (London, 1997), pp. 85–9.

per second. The resultant data, assembled into a document called a *point cloud*, can then be registered, or linked, to additional point clouds acquired in different areas to create a highly accurate spatial map of the building (Figure 15.1).⁸

Spatial archaeology is revolutionary: unlike the intuitive arguments of Branner, Severens, and Henriët, or even the indispensable yet necessarily approximative techniques of structural modelling (for which, incidentally, there is little accord as to the most appropriate for use with historic masonry structures), it supplies, for the first time, extremely precise information about the actual structural behaviour of a medieval building – a record of the passage of force forever imprinted in stone and mortar.⁹ Let us now briefly examine how spatial archaeology might be used to address a longstanding art-historical problem at the cathedral of Notre-Dame in Paris.

In 1961 Robert Branner made a simple statement in the widely published volume entitled *Gothic Architecture* that would have staying power commensurate with the authority he wielded: the flying buttress, he wrote, ‘was first employed in the nave of Notre Dame at Paris shortly before 1180’.¹⁰ This was not new: Branner but crystallized a notion that had gradually come to be accepted since Marcel Aubert first grappled with Viollet-le-Duc’s complex and contradictory writings on the flying buttresses of Notre-Dame.¹¹ If the flyer were first employed in the nave, the implication was that the choir originally went without – although Viollet-le-Duc never clearly stated that this was the case. But the inference took hold, and became part of the standard narrative for the building. Popular wisdom had it that Lassus and Viollet-le-Duc had rebuilt the entire building – in the case of the flying buttresses, this happened to be true – and it was assumed that there

⁸ For more information on such machines from one of the primary manufacturers, see <http://hds.leica-geosystems.com>, accessed 7 January 2011.

⁹ Structural modelling techniques, especially those undertaken in three dimensions, depend on accurate representation of building form; it is for this reason also that spatial archaeology is able to supply essential new information. The laser scan data from a survey of Bourges Cathedral that I undertook in June of 2008, for example, which was acquired and registered, for the first time in a building of this scale, on *both* sides of the vaults, is being used by Massachusetts Institute of Technology engineering professor John Ochsendorf to better understand the complex three-dimensional thrust patterns of sexpartite vaults. For more information on current structural modelling practices see Tallon, ‘Experiments in Early Gothic Structure’, pp. 37–43; Thomas E. Boothby, ‘Analysis of Masonry Arches and Vaults’, *Progress in Structural Engineering Materials*, 3 (2001): 246–56; and Santiago Huerta, ‘Mechanics of Masonry Vaults: The Equilibrium Approach’, in P.B. Lourenço and P. Roca (eds), *Historical Constructions* (Guimarães, 2001), pp. 47–69.

¹⁰ Robert Branner, *Gothic Architecture* (New York, 1961).

¹¹ Marcel Aubert, *Notre-Dame de Paris: sa place dans l’histoire de l’architecture du XII^e au XIV^e siècle* (Paris, 1920), pp. 76, 86, 97, 102–7.

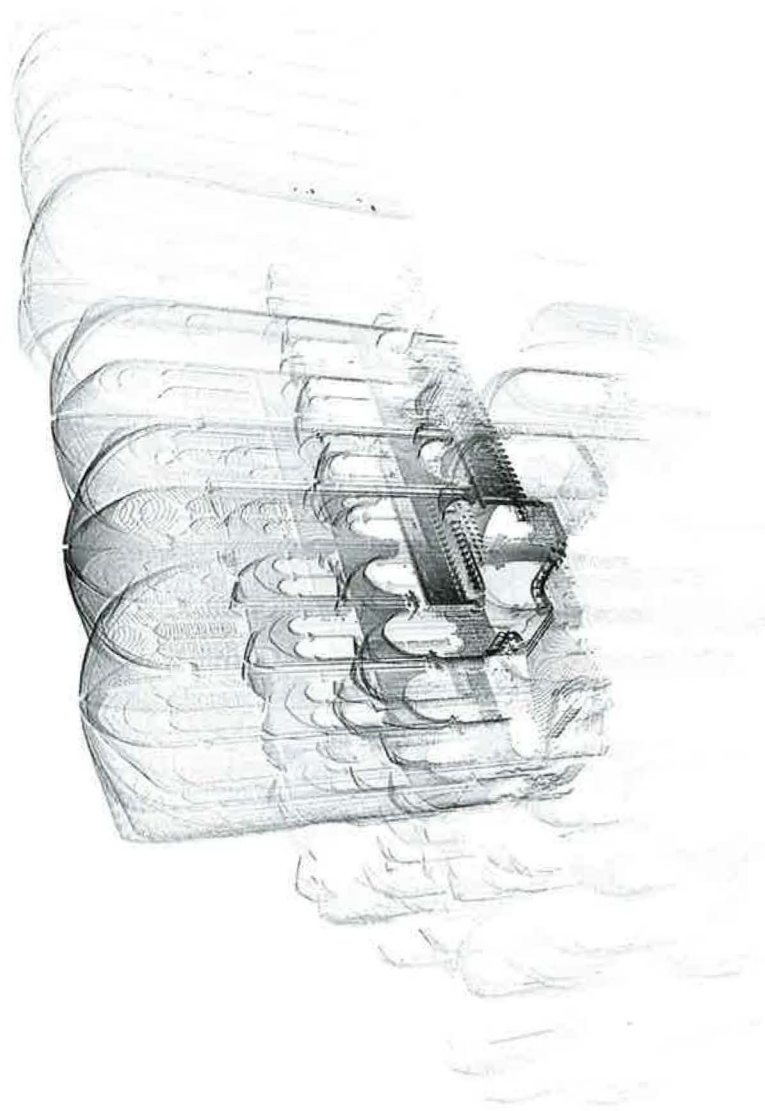


Figure 15.1 Paris, Notre-Dame, *point cloud* acquired in June 2006

was no need to look further.¹² With direct evidence seemingly gone forever, the way was paved towards art-historical invention: according to Aubert, for example, the choir had only a simple below-roof prop for main vault support.

In fact, there is considerable documentary evidence, a portion of which was presented by Stephen Murray in 1998, that, to the contrary, the choir was intended to be equipped with flying buttresses from the very start of construction in the 1160s.¹³ The evidence is preserved in textual references, drawings, images, and, despite occasionally drastic restorations, in the building itself – visible for the first time using spatial archaeology.

The original flying buttresses in the choir of Notre-Dame, to cite a little-remarked passage written in 1843 by Lassus and Viollet-le-Duc, were ‘probably like the two that still exist against the walls of the choir, on the south side, covered with stone slabs, and decorated with moderately-projecting diamond points’.¹⁴ Though demolished and rebuilt in 1846, these two flyers, located on the building at positions we will call S6 and S5 – S7 being the flying buttress in the south-west corner of the choir –, are preserved in a number of early photographs, in a plaster scale model built from 1843–48 (though with a number of errors) and, most importantly, in *attachements de maçonnerie*, measured drawings that, in this case, documented the operation of dismantling as justification for payment.¹⁵ We learn from the archives that the arch of one of the two flyers, at S5, was rebuilt in 1817.¹⁶ Thus the sole original, main-vault flying buttress remaining in the choir before the great restoration of the nineteenth century was that at S6.

¹² Reconstruction of the twenty-two flying buttresses in the choir, for example, was begun in August of 1846 in the south-west corner and finished in the north-west corner in July of 1858, as documented in the work journal of Viollet-le-Duc and Lassus, in which the daily events of the restoration campaign were recorded. See Eugène-Emmanuel Viollet-le-Duc and Jean-Baptiste Lassus, ‘Journal rédigé par l’Inspecteur en chef des travaux de restauration de la Métropole’, Charenton-le-Pont: Médiathèque du Patrimoine 80/14/10 (1844–64).

¹³ Stephen Murray, ‘Notre-Dame of Paris and the Anticipation of Gothic’, *Art Bulletin*, 80/2 (1998): 229–53; for the current state of research see Tallon, ‘Experiments in Early Gothic Structure’, pp. 147–79.

¹⁴ ‘[P]robablement comme les deux qui existent encore contre les murs du chœur, coté du midi, couvert de dalles, ornés d’une dentelure peu saillante’ – Jean-Baptiste Lassus and Eugène-Emmanuel Viollet-le-Duc, *Projet de restauration de Notre-Dame de Paris: rapport adressé à M. le Ministre de la Justice et des Cultes, annexé au projet de restauration, remis le 31 janvier 1843* (Paris, 1843), pp. 12–13.

¹⁵ The model, built by Louis Têlesphore Galouzeau de Villepin, is now housed in the Musée national des Monuments Français, Palais de Chaillot; the *attachements* for these two flyers are held at Charenton-le-Pont: Médiathèque du Patrimoine 1996/083 no. 055767 [001 and 003].

¹⁶ See Tallon, ‘Experiments in Early Gothic Structure’, pp. 163–7.

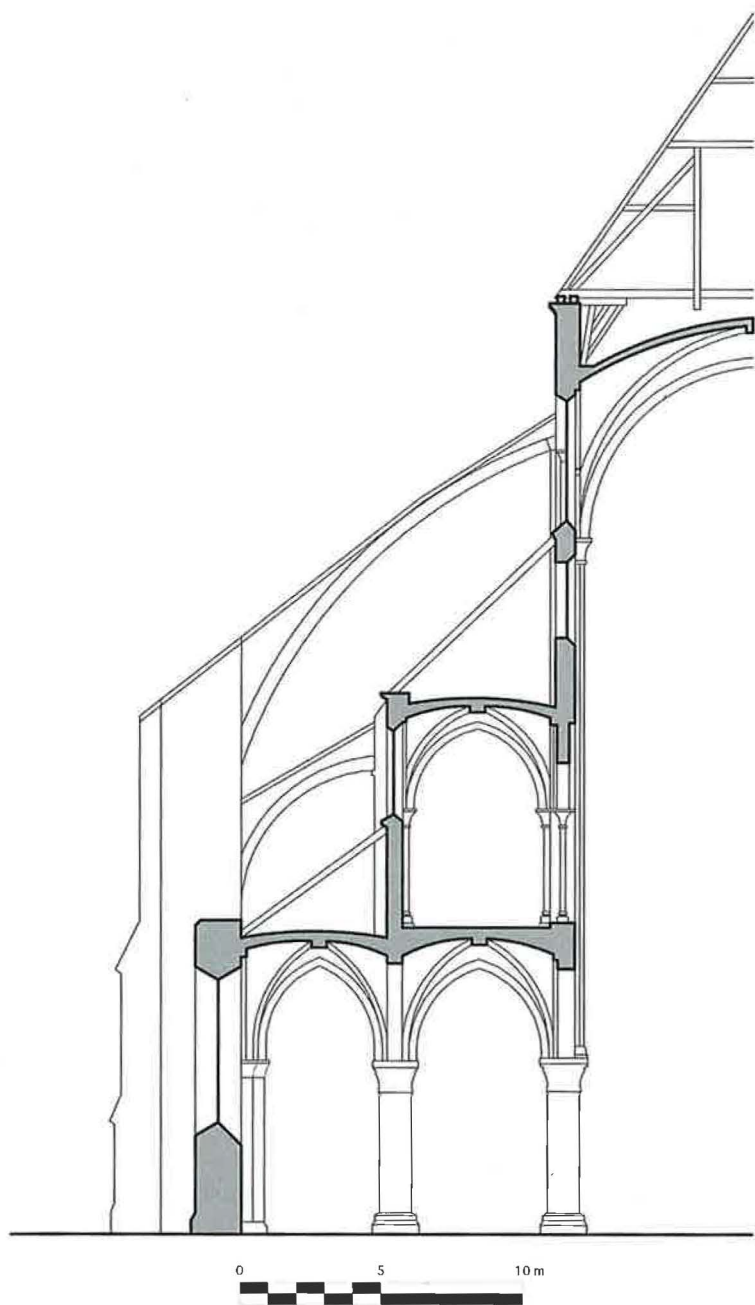


Figure 15.2 Paris, Notre-Dame, reconstruction section through S6, showing vaults through S5

Four contemporary buildings, for which evidence still exists or an earlier state can be reliably documented, stand as witnesses to the fact that the flying buttresses in the choir of Notre-Dame were assuredly not later additions: the south nave of the Burgundian cathedral of Saint-Mammès in Langres, under construction in the 1170s; the nave of Saint-Martin in Champeaux, a collegiate church in the direct possession of the bishop of Paris, begun in the 1170s as a smaller-scale partial copy of the design scheme at Notre-Dame; the choir of the Cluniac priory of Saint-Leu-d'Esserent, where a slightly modified version of the Notre-Dame flyer design was employed in the late 1170s in the context of a design change made in response to the evolving work at Notre-Dame; and finally, the nave of the abbey church of Saint-Martin at Tours, retrofitted sometime before the mid-1170s with ten-meter flying buttresses, whose likeness to the S6 flyer at Notre-Dame in terms of pitch, head shape, arch slenderness, and the disposition of the coping is striking.¹⁷

Let us now try to place this flyer in its original structural context, to understand its relationship to the vaults that it supported, using a reconstruction section through S6 (Figure 15.2).¹⁸ When the choir structure is viewed in this way, two things become apparent: despite the seemingly high placement of the flyer with respect to the transverse arch, it is more or less centred on the mass of the vault, and the slope of the flyer follows that of the lateral webs. Such flyer placement may reflect a conception of bracing that included wind loading – an average position on the upper wall designed to handle a variety of thrusts. We know nothing at all of the master builder's specific intentions, but they must have been reasonably well founded, given that this flyer managed to survive until demolished in 1846 and might have lasted even longer had it not been neglected during the several decades after the Revolution – and then subjected to a draconian formal homogenization by Lassus and Viollet-le-Duc.¹⁹

¹⁷ See *ibid.*, pp. 161–2, 178–9, and 200–205.

¹⁸ The section is based on the pre-demolition drawing of flyer S6 (Charenton-le-Pont: Médiathèque du Patrimoine 1996/083 no. 055767 [001]); a section through the nave by Adrien Chancel of 1887 (Charenton-le-Pont: Médiathèque du Patrimoine 1996/083, no index); and three-dimensional cloud data acquired in June 2006. In order to make the correlation between the interior and exterior faces of the building, a photogrammetric survey of the south flank of Notre-Dame produced in 1981 by the Institut Géographique National (Charenton-le-Pont: Médiathèque du Patrimoine 96/91 S.557) was superimposed on the data points for the vaults; alignment was made using the window tracery. This permitted the exact location of the flyer heads with respect to the vaults. The roof truss is based on *Les charpentes du XIe au XIXe siècle: typologie et évolution en France du Nord et en Belgique*, ed. Patrick Hoffsummer (Paris, 2002), pl. 15a.

¹⁹ That the *culées* at S5 and S6 (and the flyer arch at S6) survived as long as they did may be due to the fact that they were posed on the buttresses to which the two-storey passage leading to Bishop Maurice de Sully's palace to the south of the cathedral was attached. Because the episcopal

The builder of the flying buttresses of the choir at Notre-Dame had other structural tools at his disposition. The roughly 70 cm deep upper clerestory wall is composed of ashlar blocks consolidated from above by the considerable weight of a large wooden roof covered with lead.²⁰ The builder may have consciously depended on this friction-bound mesh to diffuse the thrust of the vaults; the specific placement of the flyer heads would thus have been of less concern. And the top of this wall, extended vertically in the thirteenth century (and heavily reworked in the nineteenth-), originally terminated in a set of three bands of billet moulding that were corbelled outwards to provide broader footing for the roof, and whose courses were interlocked with iron cramps. The choir was thus encircled with what Viollet-le-Duc called 'a powerful chain': the flying buttresses were not the only means of upper wall support.²¹

The form of the flyer arch at S6 is enigmatic. It is the thinnest, with respect to length, of all known twelfth-century flying buttress arches, and among the steepest. Was it too thin? Did its counterparts, which we assume were similarly disposed about the choir, fail and require replacement? The rebuilding of the arch at S5 in 1817, and a change in coping angle in the pre-demolition drawing, suggest as much, as if the upper wall had been translated outwards by vault thrust, with the resulting displacement absorbed not by an outward rotation or failure in the culée, but rather by the compression, and upward buckling, of the flyer.

And yet the laser scan reveals that the original flying buttresses of the choir of Notre-Dame did their job well. According to the laser survey, each straight-

passage was built with the chevet, its walls – narrower, for they had a different purpose – were probably interconnected with the buttresses at S6 and S5. When Jean de Chelles began to extend the western choir buttresses in the 1250s he may well have left these walls in place, modifying only the interface of the passage with the gabled outer chapel wall. It is possible then that Jehan Ravy, charged with the reconstruction of the choir flyers in the 1320s, left the twelfth-century culées intact because the walls that extended beyond the twelfth-century buttresses below, whose precise state before the intervention of Soufflot in the eighteenth century is poorly documented, were deemed unsuitable for the support of the deep *culée* he intended to use. The inviolability of the *culées* at S6 and S5 was further assured when Jacques-Germain Soufflot replaced the medieval passage, which in 1243 had been consigned to the Chapter for use as a sacristy and treasure, with a new sacristy, which directly abutted the south face of *culées* S6 and S5. See Tallon, 'Experiments in Early Gothic Structure', pp. 160–61.

²⁰ On the tensile resistance of vertically loaded horizontal bedding planes set in mortar see Paquet, 'Structures des monuments', p. 171. The weight of the lead alone, as replaced by Cardinal Louis-Antoine de Noailles in 1726, was 220,240 pounds; see M. Charpentier, *Description historique et chronologique de l'église métropolitaine de Paris* (Paris, 1767), p. 17.

²¹ '[U]n puissant chaînage' – Eugène-Emmanuel Viollet-le-Duc, 'Chaînage', *Dictionnaire raisonné de l'architecture française du XIe au XVIe siècle* (10 vols, Paris, 1854–68), vol. 2, p. 400.

bay main-vault respond, measured at a point just below the high capital, has remained almost perfectly in plumb with respect to a similar point just above the main arcade capital. Had the flying buttresses been absent during the critical first few years before complete mortar hardening, the outward thrust of the vaults – present, if difficult to quantify – would very likely have pushed apart these tall, thin walls, despite the presence of the iron cramps in the cornice.

In fact, the upper wall of the choir at Notre-Dame has been translated inward in certain bays – something entirely invisible to the naked eye.²² Each flying buttress generated a horizontal thrust against the clerestory wall due to self weight of 65 kilonewtons, or 6.6 metric tons. Had this force been applied to a still-unvaulted vessel, whose upper walls benefitted only from the resistance afforded by the roof trusses and the centring built in anticipation of vaults, the combined force of the flyers might well have caused such displacement.

Contemporary chronicler Robert de Torigny noted that the choir at Notre-Dame was completed ‘excepto majori tectorio’, but for the ‘great covering’, the vaults, by 1177.²³ Given the combined evidence of photographs, documents, and spatial archaeology – which brings precise information about building behaviour to bear on arguments that have for too long been dependent on conjecture –, we can conclude that the flying buttresses of the choir were in place by the mid-1170s.

²² To my knowledge the only published observation of the deformation at Notre-Dame was made in 1972 by François Loyer, who claimed that the clerestory wall in the choir was ‘considerably deformed’ *outward* by the thrust of the vaults – which he took as proof of the later addition of the flyers. He was mistaken by the S-curve deformation of a vessel in which tribune vaults, unbraced, press inward at mid-level, which could indeed make it seem, to the naked eye, that the clerestory above was thrust beyond plumb in the opposite direction. See Loyer, ‘Notre-Dame lavée’, *L’Oeil*, 208 (1972): 21

²³ See Francis Salet, ‘Notre-Dame de Paris, état présent de la recherche’, *La sauvegarde de l’art français*, 2 (1982): 100.