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# INDEX

# THE TEMPLE OF ZEUS AT STRATOS: NEW OBSERVATIONS ON THE BUILDING DESIGN[1]

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## 1. Introduction

The proportional relationships of the various elements in Greek Doric buildings underwent a gradual shift during the Classical and Hellenistic periods. Most evidently this change can be observed in the column and entablature proportions of monumental architecture: Hellenistic buildings have quite slender columns and clearly lower entablatures compared to their predecessors which results in a radically different appearance of the facade.[2] Most architectural scholars agree that simple arithmetical proportions are a key to understanding Classical and Hellenistic architectural design, but there is far less consensus whether the Doric design system can be regarded as being based on a fixed-size module[3] and what was the range of foot units

[1] The permission to carry out the fieldwork was granted by the Hellenic Ministry of Culture, and the fieldwork at Stratos was greatly facilitated by the friendly co-operation of the Sixth Ephorate of Prehistoric and Classical Antiquities at Patras. The research has been funded by the Emil Aaltonen Foundation, the Finnish Archaeological Institute at Athens and Royal Holloway, University of London; the three-dimensional computer model of the building was financed by the Finnish Institute at Athens. The members of the research group were T. Pöyhiä, E. Tikkala and R. Vaara; Dr P. Pakkanen and an anonymous referee have read an earlier version of the manuscript and given valuable comments. I wish to gratefully acknowledge the help and support of all these institutions and individuals.

[2] See e.g. A. W. Lawrence & R. A. Tomlinson, *Greek Architecture,* New Haven & London 1996[5], 151; M.-C. Hellmann, *L'architecture grecque* 1. *Les principes de la construction,* Paris 2002, 136–45.

[3] For a recent summary on arithmetical proportions and modularity of Greek design, see M. Wilson Jones, "Doric Measure and Architectural Design 2: a Modular Reading of the

used in the Hellenic world.[4] In order to better understand the principles of building design and the relationship between tradition and innovation in Late Classical and Early Hellenistic architecture, it is necessary to carry out new detailed investigations of individual buildings: the target of this study is the Doric temple of Zeus at Stratos in Western Greece (Fig. 1).

**Fig. 1.** The temple of Zeus at Stratos from the east. J.P. 2000.

The temple is one of the most important Early Hellenistic buildings in mainland Greece, and even though it is located on the north side of the Gulf of Corinth, stylistically it is very close to Peloponnesian Late-Classical

Classical Temple", *AJA* 105 (2001) 675–84. It should be noted here that I do not think that Wilson Jones' approach to the question of modular design is methodologically sound. The shortcomings of the paper are actually shared by the majority of traditionally orientated architectural studies on Greek design and metrology: since they rarely employ appropriate quantitative methods needed to solve the questions at hand, their results must remain tentative (cf. Section 5 of this paper, esp. n. 63).

[4] As Coulton noted already in the 1970s, "the assumption that only two foot-standards were used throughout the Greek world needs to be proved, not just accepted, and the chaotic situation in other branches of Greek metrology suggests that this is unfounded"; J. J. Coulton, "Towards understanding Greek temple design: the stylobate and inter-columniations", *ABSA* 69 (1974) 62.

architecture.[5] It was built of local white limestone, but the ambitious building project was never completed: for example, the columns were not fluted and the individual drums still retain their projecting bosses (Fig. 2). They were necessary for manoeuvring the heavy blocks during the critical lifting phase.

**Fig. 2.** The temple of Zeus at Stratos. Column drums. J.P. 2000.

The krepis of the temple is nearly entirely preserved to the level of the first step, as is the second step on the east front and the north side of the temple; only fourteen blocks of the stylobate and five bottom drums remain *in situ* in the north-east corner. The lower courses from the cella have fared the destruction of the temple and recycling of its building material rather better: the porch stylobates and the cella wall toichobate blocks are entirely preserved, as are all four anta orthostates. The cella wall orthostate blocks remain only at the pronaos end of the building; the foundation blocks of the cella floor are mostly in place, but none of the stylobate blocks carrying the

[5] For example, the proportions of the Stratos capitals have very close parallels in the Tholos at Epidauros, the temple of Athena Alea at Tegea, and the temple of Zeus at Nemea; see J. Pakkanen, *The Temple of Athena Alea at Tegea. A Reconstruction of the Peristyle Column,* Helsinki 1998, 35, table 5.

interior order have been discovered at the site.[6]

The short plan of six by eleven columns is very typical for a fourth-century Doric building (Fig. 10).[7] A representative sample of the exterior order blocks has been preserved for reconstructing the exterior Doric order rather precisely (Fig. 7), but no traces of the interior columns have been found in the excavations; since there are several fragmentary interior architrave and geison blocks,[8] it is very probable that all the interior columns were dismantled and transported away to be reused in another building.

The economic and political reasons behind the interruptions of ancient building projects are in most cases unknown,[9] and for regions such as Acarnania there are few literary sources which could clarify the situation. The temple building at Stratos was part of large urban development project of the polis, but any detailed discussion of the economy of the area in the fourth century BC must wait for the publication of the results of the Stratiké Surface Survey Project.[10]

The unfinished nature of the monument provides an interesting testing ground for combining traditional archaeological fieldwork with new methods of reconstructing the physical appearance of the building and studying fourth-century architectural design. In this paper I will first present a brief summary of archaeological work carried out in the sanctuary since nineteenth century. The middle sections concentrate on the exterior and porch columns of the building: First, how can the building height be reconstructed on the basis of archaeological material? Secondly, how can the curving taper, entasis, of the pronaos and opisthodomos columns be studied from drum measurements? The height range of the building is calculated using a computer-intensive statistical method. It is also suggested

[6] F. Courby & Ch. Picard, *Recherches archéologiques à Stratos d'Acarnanie,* Paris 1924, esp. pl. 3.

[7] Knell lists nine parallels; H. Knell, "Dorische Ringhallentempel in spät- und nach-klassischer Zeit", *JDAI* 98 (1983) 207–22, 230.

[8] Courby & Picard (above n. 6) 68–80.

[9] Th. E. Kalpaxis, *Hemiteles. Akzidentelle Unfertigkeit und "Bossen-Stil" in der griechischen Baukunst,* Mainz am Rhein 1986, 17–18.

[10] For a brief discussion of the urban development of Stratos, see end of Section 3 in this paper; for a preliminary discussion of the survey project, see F. Lang, "The Dimensions of Material Topography", in J. Isager (ed.), *Foundation and Destruction. Nikopolis and Northwestern Greece*, Athens 2001, 205–21.

that the original plans for the temple were changed in the middle of the building project by reducing the height of the columns by one drum. The final main section of the article centres on the question of whether the building design can be derived from plan and facade dimensions. The quantitative evaluation is based on cosine quantogram analysis; after the initial analysis of the building measurements, Monte Carlo computer simulations are used to test the probability of the obtained results.

## 2. Archaeological work in the sanctuary

W. M. Leake was the first known western traveller to visit the ancient remains of Stratos in 1805, and L. Heuzey was the first person to map the walls and the remains of a Doric temple on a projecting platform of the western stretch of the walls in 1856.[11] Archaeological excavations at Stratos have a history of more than a century: A. Jaubin of the French School at Athens (École française d'Athènes) started work at the temple site already in 1892: the discovered inscriptions and a brief note of the conducted work were published in 1893,[12] but the survey notes made by A. Tournaire on the architecture of the building were subsequently lost and never published.[13]

F. Courby, Ch. Picard and R. Vallois continued the French work at the site in 1910; more limited test trenches and studies of the cella interior were carried out in 1911 by Picard and Ch. Avezou and in 1924 by Picard and J. Replat.[14] Their book appeared in print the same year as the final season of work on the temple was conducted, but the publication was not without controversy: Courby and Picard felt that A. K. Orlandos' long and nearly simultaneously published article on the temple exploited the French

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[11] W. M. Leake, *Travels in Northern Greece* vol. 1, London 1835, 137–43; L. Heuzey, *Le mont Olympe et l'Acarnanie. Exploration de ces deux regions, avec l'étude de leur antiquités, de leur populations anciennes et moderne, de leur géographie et de leur histoire,* Paris 1860, 331–45, pl. 8. Heuzey's plan is reproduced in Courby & Picard (above n. 6) fig. 2.

[12] A. Jaubin, "Inscriptions de Stratos", *BCH* 17 (1893) 445–52; Th. Homolle, "Nouvelles et Correspondance", *BCH* 17 (1893) 213–14.

[13] Courby & Picard (above n. 6) 8.

[14] Courby & Picard (above n. 6) 8–9.

work at the site and they also clearly express this in the monograph.[15]

N. Norman carried out a restudy at the temple site as part of her research on fourth-century cella interiors in the 1970s,[16] but the relatively few archaeological remains of the interior order had already been well covered by Courby and Picard.[17] Most recently, the Sixth Ephorate of Prehistoric and Classical Antiquities and the German Archaeological Institute have conducted extensive research in and around Stratos.[18] From the point of view of the temple architecture, the most important result of the surface survey was the discovery of the ancient limestone quarries to the north-west of the city.[19] E.-L. Schwandner and L. Kolonas also carried out a study on the platform of the sanctuary of Zeus and the city wall projecting to the north and south of the temenos; they came to the conclusion that the temple was built at the end of the fourth century BC on top of a fifth-century predecessor.[20]

The Finnish research group carried out two seasons of fieldwork in the sanctuary of Zeus in 2000 and 2001. The most important aim of this research has been to clarify problems related to the reconstruction of the temple of Zeus by means of carrying out building measurements at the site: for example, Courby and Picard's estimate of the building height is based as much on their idea of 'correct' column proportions as on actual blocks at the site.[21] The main emphasis of the first season was on column drums: 113

[15] Courby & Picard (above n. 6) 9–10; even though the journal in which Orlandos' article was published is dated to 1923, it did not appear before 1925: e.g. the clearing of the cella done in 1924 by the French is taken into account in the study; A. E. Orlandos, "Ὁ ἐν Στράτῳ τῆς Ἀκαρνανίας ναὸς τοῦ Διός ", *AD* 8 (1923) 1–51.

[16] N. Norman, *The "Ionic" Cella: a Preliminary Study of Fourth Century B.C. Temple Architecture,* unpublished PhD thesis, Univ. of Michigan 1980.

[17] Courby & Picard (above n. 6) 59–82.

[18] E.-L. Schwandner, "Spáthari – Tempel ohne Säule und Gebälk?", in E.-L. Schwandner (ed.), *Säule und Gebälk. Zu Struktur und Wandlungsprozeß griechisch-römischer Architektur,* Mainz 1996, 48–54; P. Funke, "Acheloos' Homeland. New Historical-Archaeological Research on the Ancient Polis Stratos", in J. Isager (ed.), *Foundation and Destruction. Nikopolis and Northwestern Greece*, Athens 2001, 189–203; Lang (above n. 10) 205–21.

[19] Funke (above n. 18) 196, fig. 6; Lang (above n. 10) 206, fig. 12.

[20] E.-L. Schwandner & L. Kolonas, "Beobachtungen am Zeusheiligtum von Stratos", *MDAI(I)* 16 (1996) 187–96.

[21] Courby & Picard (above n. 6) 25–29, 41. The danger of not taking into account the

column drums and 11 capitals were measured. During the second season we concentrated on the cella wall and anta blocks. A sample of block drawings by architect T. Pöyhiä is illustrated in Figs. 3–4 and the right half of Fig. 8.

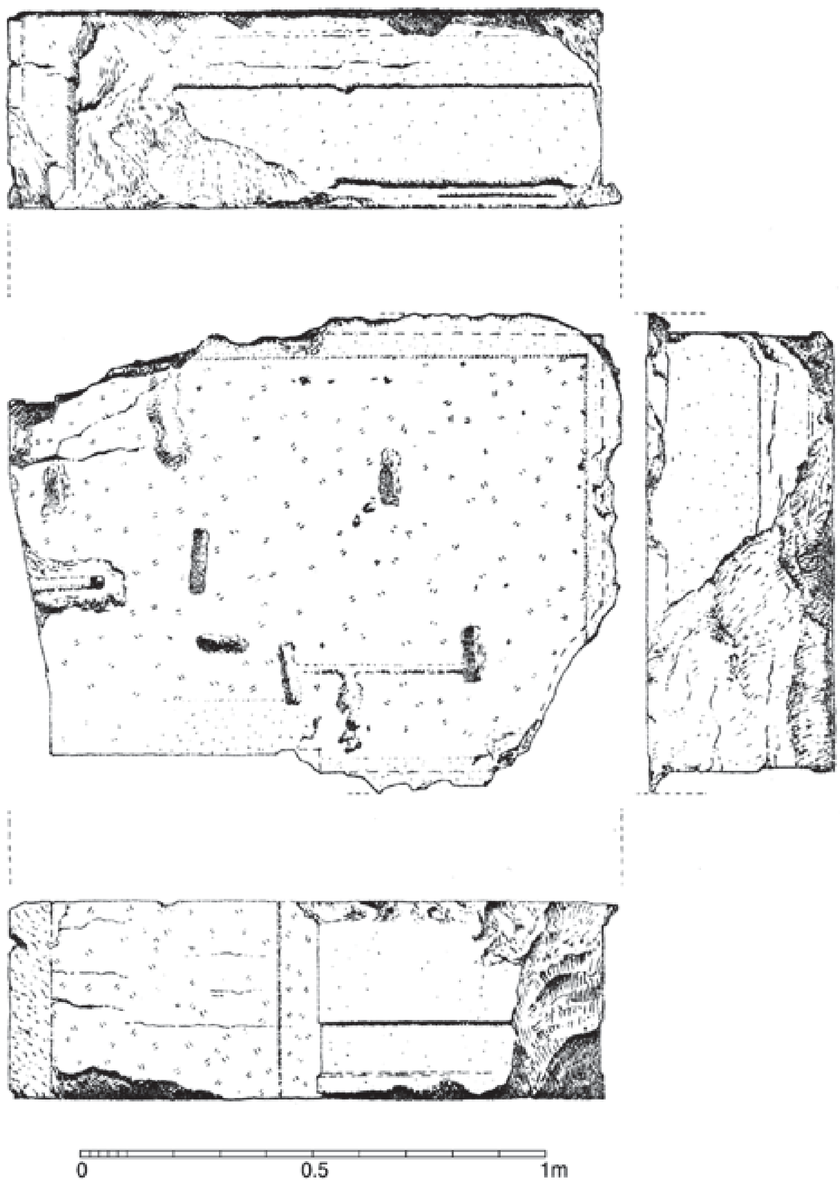


**Fig. 3.** The temple of Zeus at Stratos. Anta capital. T. Pöyhiä 2001.

primary nature of the archaeological material is well illustrated by the 4th-century Tholos at Delphi: Amandry and Bousquet were able to convincingly show in the 1930s that the column should be reconstructed with five and not four columns as had been previously thought; however, this reconstruction was rejected by Dinsmoor only because the four-drum shaft fitted better his view of 4th-century architectural proportions; P. Amandry & J. Bousquet, "La colonne dorique de la Tholos de Marmaria", *BCH* 64–65 (1940–41) 121–127; W. B. Dinsmoor, *The Architecture of Ancient Greece,* London 1950[3] (1975) 234 n. 3.

## 3. Reconstructing the building height

Calculating the building height from the preserved blocks is not as straightforward as is often presented in architectural studies which give the building dimensions with millimetre precision. Quantitative methods can help to define the limits of our knowledge, but archaeological material rarely fulfils the two assumptions required for carrying out classical confidence interval calculations for the average block height: the original 'population' of building blocks should be normally distributed and the preserved sample random. However, computer-intensive statistics can be employed to find a probable range for the building height.[22]

The 30 peristyle columns of the temple were constructed with nine drums in each shaft, and currently 61 drums at the site have their full height preserved. The height variation is significant: the shortest drum measures only 0.604 m and the tallest 1.216 m. Using the bootstrap-*t* method with finite population correction factor the 95% confidence interval for the drum mean height cannot be determined more accurately than as 0.804–0.859 m[23]

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[22] Pakkanen (above n. 5) 49–62. I have calculated the confidence intervals presented in this paper using the bootstrap-*t* (studentised) method. A 95% confidence interval for the drum height means that there is a 95% probability for the real mean drum height being within the determined range. The basic principle behind bootstrap methods is that since the existing sample provides the best knowledge of the studied phenomenon, the sample can be used as a guide to the population distribution. Technically, this involves taking several random resamples of the sample with replacement in order to approximate the confidence interval range. I have chosen to use the bootstrap-*t* method because it does not require that the original population is normally distributed. For a recent review of the archaeological applications of bootstrap methods, including an assessment of the Tegea analysis presented in Pakkanen (above n. 5) 53–54, see M. Baxter, *Statistics in Archaeology,* London 2003, 148–153. The discrepancy of 2 mm noted by Baxter between the bootstrap-*t* confidence interval in the original Tegea publication and his recalculation is well within the error margin of drum measurements; also, variation of this magnitude can often be observed between separate bootstrap runs of the drum data. On bootstrap methods in general, see B. F. J. Manly, *Randomization, Bootstrap and Monte Carlo Methods in Biology,* London, Weinheim, New York, Tokyo, Melbourne and Madras 1997$^2$, 34–68 and A. C. Davison and D. V. Hinkley, *Bootstrap Methods and Their Application,* Cambridge 1997.

[23] The formula used to calculate the *t*-statistic was $T_B = (\bar{x}_B - \bar{x}) / (s_B/\sqrt{n})$, where the sample mean $\bar{x} = 0.8296$ m and sample size $n = 61$; $\bar{x}_B$ and $s_B$ are calculated for each bootstrap sample. The values limiting 95% of the distribution were $t_{\alpha/2} = 1.868$ and $t_{1-\alpha/2} = -2.140$. The confidence interval can be calculated as

and for the whole column, capital included, as 7.73–8.24 m.[24]

However, the variation in the height of the cella wall and anta blocks (Fig. 3) is much smaller, and the confidence interval for one course can be calculated as 0.398–0.402 m.[25] Since the exterior order of the temple and the cella wall are architecturally tied together by beams and coffers, the cella wall can be used to define the height of the peristyle column more precisely than solely on the basis of column drums. The height of the cella wall up to the anta capital level – which is also the total height of the porch columns – can be established as 7.25–7.31 m[26] and the height of the peristyle column as 7.88–7.93 m.[27]

The calculations above are based on the preserved archaeological material, and, interestingly, Courby and Picard's suggestion for the exterior column height of 7.908 m falls inside the determined statistical confidence interval.[28] As has been noted above, the French estimate was largely based on their idea of Classical column proportions. Since the number of blocks in

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$$\bar{x} - t_{\alpha/2}\ (s/\sqrt{n}\sqrt{(N-n)/N}) < \mu < \ \bar{x} - t_{1-\alpha/2}\ (s/\sqrt{n}\sqrt{(N-n)/N})\ ,$$

where the sample standard deviation $s$ = 0.12334 and the population size $N$ = 270 (original number of drums). From the formula we obtain the confidence interval 0.804–0.859 m. Since the $t$-statistic $T_B$ was calculated without using the finite population correction factor it is justified to introduce it in the confidence interval calculations (on the factor, see e.g. S. Shennan, *Quantifying Archaeology,* Edinburgh 1997$^2$, 363–65). The random numbers used in the generation of the $t_B$ values are produced with statistical program Survo's *rand*($n_s$) function ($1 \le n_s \le 2^{32-1}$) using INSEED and OUTSEED specifications (the function has been implemented by S. Mustonen; the numbers are generated according to Combined Tausworthe method; the period length of *rand* is about $10^{18}$). For the bootstrap-*t* formulae, see Manly 1997, 56–58, and for the program used in bootstrapping, see Pakkanen (above n. 5) p. E1 in app. E.

24 There are five exterior order capitals preserved at Stratos; their height range is 0.492–0.510 m with a mean height of 0.502 m.

25 Their height range of the blocks is 0.379–0.437 m; $\bar{x}$ = 0.3996 m; $n$ = 78; $s$ = 0.0090; $N$ = 554 (original number of cella wall anta blocks); $t_{\alpha/2}$ = 1.876; $t_{1-\alpha/2}$ = –1.996. The formula for calculating the confidence interval is the same as in n. 23 above.

26 Height of the orthostate (1.285 m) plus 15 wall blocks gives a range of 7.253–7.308 m.

27 The height difference of the peristyle and porch stylobates (0.05 m) + cella wall up to anta capitals + cella entablature height (2.038 m) – peristyle frieze backer height (0.640 m) – architrave height (0.825 m) = 7.876–7.931 m; cf. Courby & Picard (above n. 6) 42, fig. 20 & pl. 10.

28 The estimated height varies slightly in Courby & Picard (above n. 6): on p. 29 the height is given as c. 7.90 or 7.94 m, and on p. 42 as 7.908 m.

the cella wall limits how the exterior colonnade can be reconstructed, Courby and Picard had to choose between various alternatives: the lowest option gave a column height of 5.45 times the lower shaft diameter, the middle 6.06 diameters and the highest 6.77 diameters.[29] They do not discuss the matter any further but just note that considering the apparent date of the building, only the second alternative is plausible.[30]

Does the new fieldwork merely confirm that Courby and Picard were correct in their quick dismissal of the other alternatives? I would not be that hasty. A column height in the range of 6.5–7.0 times the lower diameter would fit better the comparative material from the Early Hellenistic period, while a proportion closer to 6 lower diameters is quite typical for early and mid-fourth-century buildings. The proportional taper of the column shaft is even more anomalous: for the unusually strong taper of 3.8% at Stratos I have found only one parallel in mid-fourth-century Doric architecture and none in later.[31]

The discrepancy could perhaps be explained by a closer study of the preserved material at Stratos and comparative material from other sites. Figure 4 presents a drawing of one of the exterior capitals superimposed on a top drum. The diameter difference between the ninth drum and the capital is approximately 10 cm,[32] a situation which does not have a parallel in other unfinished Doric monumental buildings in the mainland or the islands.[33] The fourth-century Archilocheion on Paros gives a more typical example of

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[29] Courby & Picard (above n. 6) 29.

[30] Courby & Picard (above n. 6) 29; they argue later in their study that the date of the building is c. 330 BC; *ibid.* 85–87.

[31] Taper of the column shaft at Stratos: 100% – (lower column diameter 1.29 m – upper column diameter 1.01 m) / (column shaft height 7.4 m) ≈ 3.78%. For the comparative material, see Pakkanen (above n. 5) 72–73; J. Pakkanen, "The Column Shafts of the Propylaia and Stoa in the Sanctuary of Athena at Lindos", *Proceedings of the Danish Institute at Athens* 2 (1998) 155–57.

[32] The upper diameter is possible to measure on seven top drums and the mean is 1.110 m (range 1.098–1.120 m); the two well preserved capitals have lower diameters of 1.007 and 1.015 m measured on the arrises.

[33] In the unfinished temple at Segesta there is considerable variation between the capital and column shaft diameters, but both the capitals and shafts are unfluted, and the bottom of the capital neck has a strongly projecting protective band at the bottom; D. Mertens, *Der Tempel von Segesta und die dorische Tempelbaukunst des griechischen Westens in klassischer Zeit,* Mainz am Rhein 1984, fig. 6, pl. 27, insert 20.

Greek building practices (Fig. 5): the slightly recessed band at the top of the unfinished drum matches almost exactly the diameter of the capital neck. The stage at which work on the columns was interrupted is the same as at Stratos: the capitals are finished but the drum surfaces are only roughly worked out with a point and the bosses have still been left in place.[34] Fifth-century Doric buildings followed the same practice: the exterior columns of the peripteral temple of Apollo on Delos have a difference of 3.1 cm between the top of the unfinished drum and the capital neck, but in the porch column it is only 0.2 cm;[35] in the unfinished double stoa at Thorikos the difference is 2.9 cm,[36] and in the small peripteral temple of Nemesis at Rhamnous 0.7 cm.[37]

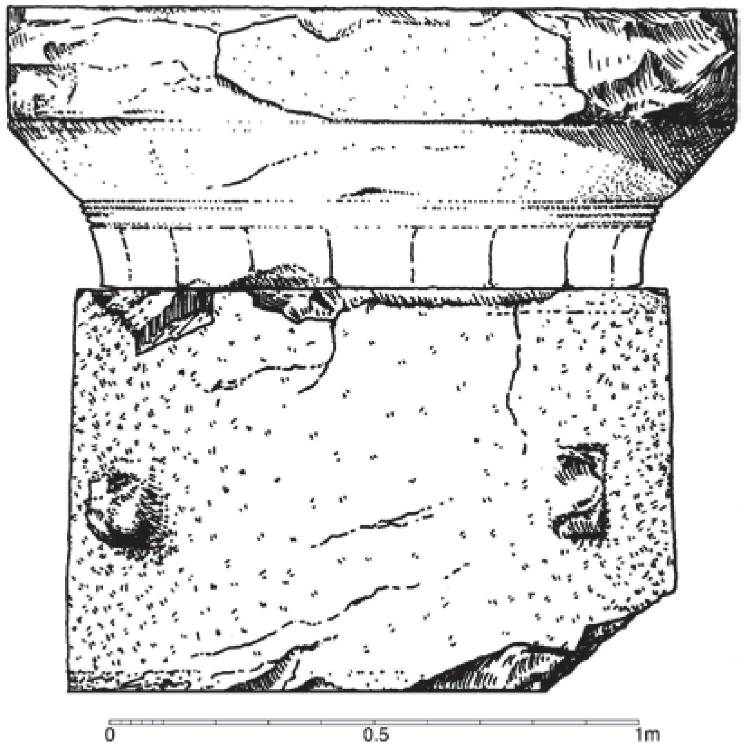


**Fig. 4.** The temple of Zeus at Stratos. Top drum and capital of the peristyle column. T. Pöyhiä 2000.

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[34] The building is dated to the middle or second half of the 4th century BC; on the building, see A. Ohnesorg, "Der dorische Prostylos des Archilocheion auf Paros", *AA* 1982, 271–90.

[35] F. Courby, *Les temples d'Apollon,* Délos 12, Paris 1931, 16, figs. 20, 23–24, 65–66.

[36] Society of the Dilettanti, *The Unedited Antiquities of Attica Comprising the Architectural Remains of Eleusis, Rhamnus, Sunium, and Thoricus,* London 1833[2], chap. 9 pl. 3 (drawing by F. Bedford).

[37] Society of the Dilettanti (above n. 36) chap. 6 pl. 4 (drawing by J. Gandy).

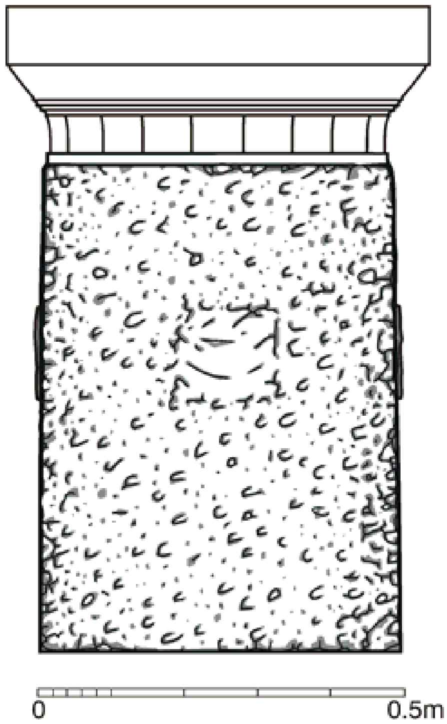


**Fig. 5.** The Archilocheion on Paros. Capital and top drum of the facade column. J.P. after Ohnesorg (above n. 34) fig. 3.

Leaving a 10-cm margin as at Stratos gives no practical advantage for working the final profile of the column shaft: on the contrary, it requires the introduction of one additional phase of carving to work out the curvature of the shaft profile before cutting the shaft fluting could have started.[38] The archaeological material of the temple of Zeus and the comparative material can be used to argue that a design change took place at Stratos in the middle of the building project. The diameter difference between the capital and the top drum at Stratos is consistent with an interpretation that one drum is missing from the executed columns: the maximum measured diminution in a ninth drum is 5 cm which leaves ample margin for fitting a tenth drum in the shaft.[39] Moreover, unfinished drums intended for the temple of Zeus have been discovered in the limestone quarries near Lepenou, just four kilometres away from the polis of Stratos.[40]

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[38] See Section 4 below on the porch column entasis; the extra amount of carving required for the exterior columns can be estimated by comparison of the peristyle columns and the further worked porch columns (cf. Figs. 4 and 8).

[39] The diminution of the ninth drums varies between 2.6–5.0 cm.

[40] Funke (above n. 18) 196. There is a clear scale difference between the larger temple and the smaller public buildings of the city.

Therefore, I propose that the temple was planned with ten drums per column shaft but the design was later changed and a lower version with only nine drums was built. Figure 6 presents a reconstruction of the temple facade as it was most probably originally intended. Based on the cella wall, the 95% confidence interval for the designed height of the exterior column can be calculated as 8.67–8.73 m, which is 6.72–6.77 times the lower diameter; the proportional taper of 3.4% is still quite strong but more in line with comparative architectural material.[41]

Figure 7 shows the facade of the building as it was executed. The photorealistic digital model incorporates the results of the new fieldwork: the biggest difference of the new reconstruction compared to the previous ones is the variation in the height of column drums and the irregular placement of the bosses.[42] The proportional height of the columns as they were carried out is 6.11–6.15 times the lower diameter.[43]

Economic factors are a very likely cause behind the design change. The temple is part of large-scale urban development at Stratos: during the last third of the fourth century BC also the civic buildings in the agora and the first phase of the theatre were constructed.[44] A temple building project such as the one at Stratos would have most likely been dependent at least partially on more or less voluntary private benefactions.[45] The building itself

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[41] Height of the orthostate (1.285 m) plus 17 wall blocks gives a range of 8.048–8.111 m; for calculation of the column height, see above n. 27. Proportional height of the column: $8.671 / 1.29 \approx 6.722$; $8.734 / 1.29 \approx 6.770$. Taper of the column shaft: $100\% - (1.29 - 1.01) / 7.9 \approx 3.41\%$. For a reference to the comparative material, see above n. 31.

[42] The model has been made by Dr Chrysanthos Kanellopoulos and his team Sixton using AutoCAD; the surface textures were rendered in 3-D Studio Max by Anaparastasis. From the detailed study of the drums it was evident that the bosses could not have been aligned on the axes of the columns as they are presented in Courby & Picard (above n. 6) pl. 8: some drums have only three bosses, and no consistent pattern was discovered between the drum dowels, the empolia and the bosses. Since the bosses would have been removed when the fluting was cut, there obviously was no need to plan their positions in a systematic way.

[43] Proportional column height: $7.876 / 1.29 \approx 6.105$; $7.931 / 1.29 \approx 6.148$.

[44] Funke (above n. 18) 193–94.

[45] The inscription *IG* IX 1, 446, dated to the late 4th or early 3rd c. BC, was discovered in the north-east corner of the temple and it gives a probable list of local subscribers to the temple project; the subscriptions vary between 10 and 60 minai. For a discussion of the inscription, see Courby & Picard (above n. 6) 87. For financing temple building in the Late Classical and Early Hellenistic periods, see A. Burford, *The Greek Temple Builders*

bears evidence that the strain of all the late-fourth-century building activity on the finances of a relatively small city was too much. If the shortage of funds became evident after the construction of columns had already been started, the most simple way of producing a fully standing building and cutting down the building costs would have been to make the building one drum shorter than originally intended.

**Fig. 6.** The temple of Zeus at Stratos. Reconstruction of the facade as planned. J.P.

## 4. Porch column entasis

The columns of the two porches, the pronaos and the opisthodomos, were worked one step further than the peristyle columns: the bosses had been

*at Epidauros. A Social and Economic Study of Building in the Asklepian Sanctuary, During the Fourth and Early Third Centuries B.C.,* Liverpool 1969, 35–38, 81–85. For general discussions on funding, see J. J. Coulton, *Ancient Greek Architects at Work. Problems of Structure and Design,* Ithaca, N.Y. 1977, 20–21; Hellmann (above n. 2) 56–66.

carved off, and the drums from these four columns can therefore yield further information on the design of entasis, the gentle curvature of the column shafts.

Eleven of the original 28 drums are preserved, and the side elevations of the best preserved seven drums are illustrated on the right of Figure 8. It is unlikely that they originally belonged to the same column, but the differ-

**Fig. 7.** The temple of Zeus at Stratos. Reconstruction of the facade as executed. Ch. Kanellopoulos, J.P., Sixton & Anaparastasis.

ences between the four columns were very small, as is evident from the good fit between the measured drum dimensions and the fitted curve on the left side of Figure 8: in the graph the curvature of the shaft profile is greatly exaggerated by stretching the *x*-axis; the actual measured points of the profile are plotted as circles.

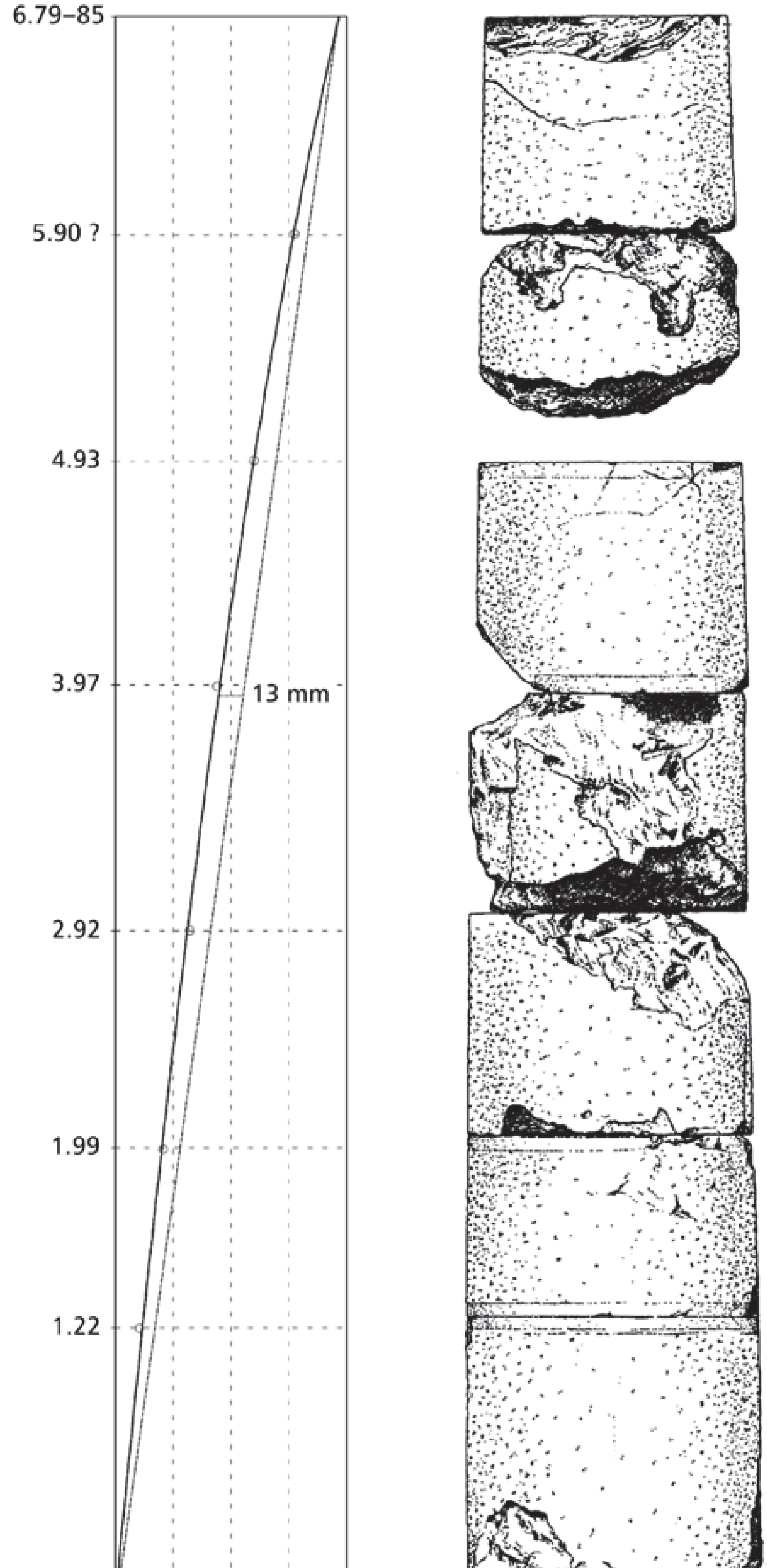


**Fig. 8.** The temple of Zeus at Stratos. Profile of the porch column. Diagram by J.P., drawing by T. Pöyhiä 2001

Mathematical modelling can be used to determine the maximum projection of the entasis.[46] The exact height of the porch column shafts is not known since no capital from these columns is preserved at the site: the height of the shaft can be estimated as 6.79–6.85 m from the cella wall height and approximate proportional height of the capital.[47] When a cubic is fitted to the shaft profile data, the maximum entasis can be calculated as circa 13 mm, 0.2% of the column height, and it is slightly more than half way up the shaft.[48]

In fourth-century and Hellenistic Doric architecture the position of maximum entasis projection is in most cases in the centre of the shaft.[49] The small deviation at Stratos can most likely be explained by the unfinished state of the column and the fact that the drums were not originally from the same shaft. However, the preserved drums clearly demonstrate how the curvature of the shaft was taken into consideration at this stage of finishing the temple.

## 5. Design unit of the building

The relationship between an architectural design and building measurements is among the key questions in the study of Greek architecture. All attempts to try to define a module or a metrological unit of unknown size in a set of dimensions should employ an appropriate statistical method: if they do not, the risk of drawing false conclusions from the data is significant. The method used in this paper is based on D. G. Kendall's cosine quantogram analysis where the validity of the initial results is evaluated by using Monte Carlo computer simulations.[50]

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[46] J. Pakkanen, "Entasis in Fourth-Century BC Doric Buildings in the Peloponnese and at Delphi", *ABSA* 92 (1997) 323–44; Pakkanen (above n. 31) 155–57.

[47] The porch capital height can be estimated as follows: peristyle capital height (0.502 m) / height of peristyle column (7.9 m) × height of porch column (7.3 m) ≈ 0.46 m.

[48] The plotted points are (0, 0), (0.013, 1.216), (0.025, 1.985), (0.039, 2.922), (0.053, 3.966), (0.072, 4.932), (0.093, 5.902), (0.116, 6.833); the formula of the fitted curve is $y = 0.018 + 88.25x - 316.45x^2 + 534.71x^3$.

[49] Pakkanen (above n. 46) 342–43; Pakkanen (above n. 31) 155–57.

[50] On the method more in detail, see D. G. Kendall, "Hunting Quanta", *Philosophical Transactions of the Royal Society of London. Mathematical and Physical Sciences* A 276 (1974) 231–266. The effect of simulation distributions in the second stage is questioned

If a design unit of certain size, or a quantum in statistical terms, was used by the Greek architect to decide the sizes of various elements and his design was executed relatively precisely, it should be possible to detect the original design by analysing the building measurements. The quantum hypothesis is in this case that a building dimension $X$ can be expressed as an integral multiple $M$ times the quantum $q$ plus a small error component $\varepsilon$:

$$X = Mq + \varepsilon.$$

The reason why the dimension does not exactly fit the quantum is not significant from the statistical point of view: the error could equally well be a result of modern measurement errors or differences between the ancient building execution and the initial design, but in any case $\varepsilon$ should be significantly smaller than $q$. The practical result of this is that since 'errors' of ±10 mm are quite usual in Greek architecture,[51] design units as small as a dactyl or one sixteenth of a foot unit cannot be discovered in a set of architectural dimensions. This is also why taking building dimensions and expressing them in terms of hypothetical dactyls does not advance our understanding of Greek architectural design. Computer simulations can, however, be used to demonstrate that a quantum in the region of a quarter-foot can be detected.[52]

To determine if dimension $X$ can successfully be given in terms of quantum $q$, $X$ is divided by $q$ and the remainder is analysed: the closer $\varepsilon$ is to 0 or $q$, the better $X$ fits $q$. How well the dimensions cluster around the quantum can be calculated by using the formula

$$\phi(q) = \sqrt{2/N}\sum_{i=1}^{n}\cos(2\pi\varepsilon_i/q),$$

in P. R. Freeman, "A Bayesian Analysis of the Megalithic Yard", *Journal of the Royal Statistical Society* A 139 (1976) 20–35, but it can be demonstrated that the results are not significantly dependent on data modelling; see J. Pakkanen, "Deriving Ancient Foot Units from Building Dimensions: a Statistical Approach Employing Cosine Quantogram Analysis" in G. Burenhult and J. Arvidsson (eds.), *Archaeological Informatics: Pushing the Envelope. CAA 2001*, Oxford 2002, 501–506; J. Pakkanen, "The Toumba Building at Lefkandi: a Statistical Method for Detecting a Design-Unit", forthcoming in *ABSA* 99 (2004). The new software developed by the author for the analysis is also discussed in these articles.

[51] J. J. Coulton, "Towards Understanding Greek Temple Design: General Considerations", *ABSA* 70 (1975) 94.

[52] Pakkanen (2002 in n. 50) 502–503.

where $N$ gives the number of studied measurements. The maximum function score $\phi(q)$ indicates which one of the studied quanta $q$ is the most probable candidate for the design unit (Fig. 9). In the second phase of the study computer simulations are employed to determine whether this quantum actually produces a peak high enough to be considered a 'true' design unit rather than just background noise. In these simulations random sets of artificial data are created from non-quantal distributions and they are analysed exactly as the original measurement set in order to resolve the question whether a peak as high as the detected maximum function score could also be a result of non-quantal data.[53]

Three different modules and foot units have been suggested as the design unit of the temple of Zeus at Stratos: an 'Ionic' foot of 0.294 m,[54] a module of 0.316 m,[55] and a 'Doric' foot of 0.329 m.[56] I will first analyse the principal plan dimensions of the building (Table 1) and then the facade dimensions (Table 2). The reason for dividing the measurements into two sets is that it can enable a further analysis of the architectural design principles at Stratos.

In Figure 9 is presented the cosine quantogram of the building plan data. The studied range for $q$ is 0.06–0.60 m: the lower limit of the range is chosen so that it is significantly larger than the error margin of measurements and smaller than a quarter-foot of any suggested Greek foot unit, and the upper so that it is greater than the cubits corresponding to possible foot standards. The results of the cosine quantogram analysis can be presented as a single curve where the quantum score $\phi(q)$ is plotted against $q$. There is only one clear peak at 0.1053 m with a score of 4.9. The Monte Carlo computer simulations of non-quantal replica data sets indicate that a peak with a height of 3.9 or greater is significant at 5% level ($\alpha$ = 5% in Fig.

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[53] I have in previous papers suggested that kernel density estimation (KDE) distributions can be used to create the simulated non-quantal data sets; Pakkanen (2002 and 2004 in n. 50).

[54] H. Bankel, "Moduli an den Tempeln von Tegea und Stratos? Grenzen der Fussmassbestimmung", *AA* (1984) 417–20.

[55] Courby & Picard (above n. 6) 85; W. Koenigs, "Zum Entwurf dorischer Hallen", *MDAI(I)* 29 (1979) 233–34.

[56] D. Mertens, *Die dorische Tempelbaukunst des griechischen Westens in klassischer Zeit,* Habilitationsschrift München 1981, 328. See also Koenigs (above n. 55) 231 n. 45, 233, though Mertens' analysis of the Stratos facade is omitted from the final publication; see Mertens (above n. 33).

9).[57] The highest score produced in the simulations was actually 4.6, so statistically there remains very little doubt that the detected peak is not a 'true' quantum. The unit is exactly one third of the design module of 0.316 m suggested already by Courby and Picard; furthermore, the analysis does not give any support that an 'Ionic' or a 'Doric' foot would have been employed in the layout of the temple plan.[58]

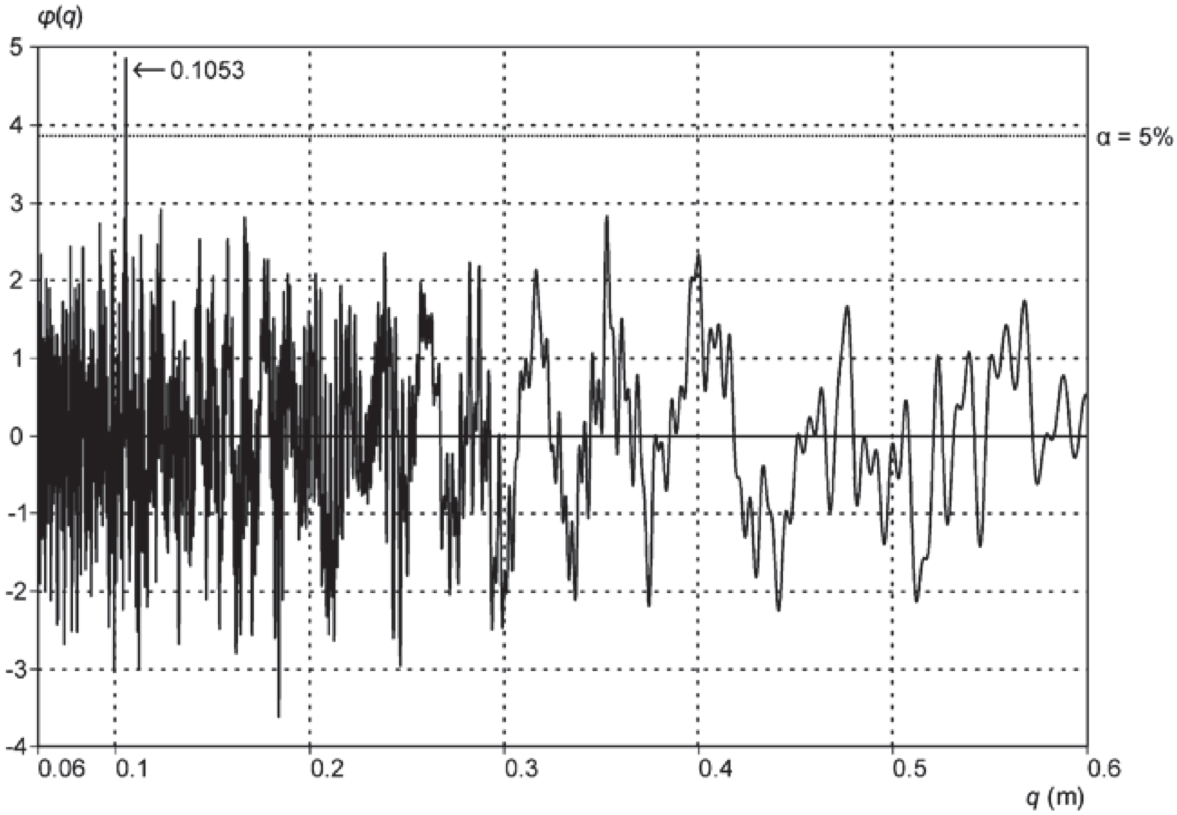


**Fig. 9.** The temple of Zeus at Stratos. Cosine quantogram analysis of the building plan dimensions. J.P.

The fit of the design unit or module to the plan dimensions is presented in Table 1. The discrepancies between the dimension expressed in terms of the detected quantum and the actual measurements are less than a

[57] A non-quantal data model based on the plan data was created using KDE with a window-width of 4.0; the 5% significance level is based on 1000 Monte Carlo simulations; on KDE and data modelling more in detail, see Pakkanen (2002 in n. 50) 502 and Pakkanen (2004 in n. 50).

[58] The principal reason why Bankel's graphic method fails to recognise the design module at Stratos is that it presupposes that all design units are possible to give as whole dactyls of the employed foot, not e.g. one third of the 'foot' as here; cf. Bankel (above n. 54) 417–20.

centimetre for nearly all the principal dimensions (col. D); the only exceptions are the cella length measured at toichobate level and the interaxial distance of the porch columns. The modular layout of the temple is further analysed in Figure 10. The most likely starting point of the architect is the distance between the axes of the columns of 30 modules; the corner interaxial is reduced by 3 modules, and the axes of the columns are set 7 modules from the stylobate edge, thus resulting in a stylobate width of 158 modules and length of 308 modules. The combined width of first and second steps of the krepis is 7 modules and the width of the euthynteria is 1 module. The outer faces of the cella antae are aligned with the centres of the second and fifth columns of the front, so the exterior width of the cella becomes 90 modules. The only place in the plan where the strict modular arrangement seems to break apart is in the positioning of the ends of the cella according to the sides of the third and ninth columns of the flanks: since the lower diameter of the column is not an exact multiple of the plan module, the distance of the cella from the front and back edges of the stylobate (*a* in Figure 10) cannot be given in terms of an integral multiple of the module.

The principal dimensions of the facade are presented in Table 2. New dimensions of the peristyle column based on the Finnish fieldwork at the site are given in bold typeface; the height of the column is omitted because it cannot be determined precisely enough for the purposes of design unit analysis. The maximum peak of the cosine quantogram of the facade data is precisely at the same place as in the plan analysis, but with a score of 4.1 it is substantially lower than in the first analysis (Fig. 11). The peak is still clearly statistically significant: the computer simulations place the 5% significance level in this case at 3.7.[59] The reason for the lower peak is clear on the basis of Table 2: with the exception of lower column diameter, all facade dimensions at building plan level have a discrepancy of less than a centimetre, but the general fit of the other facade elements is discernibly worse.

The statistical analyses of the building dimensions of the temple of Zeus at Stratos have also a more general significance for the study of Greek architectural design. It is generally accepted that fourth-century and later Ionic temples had a strictly modular plan, but the same transparency cannot

[59] A KDE distribution with a window-width of 0.45 was used to produce the 1000 non-quantal simulation data sets.

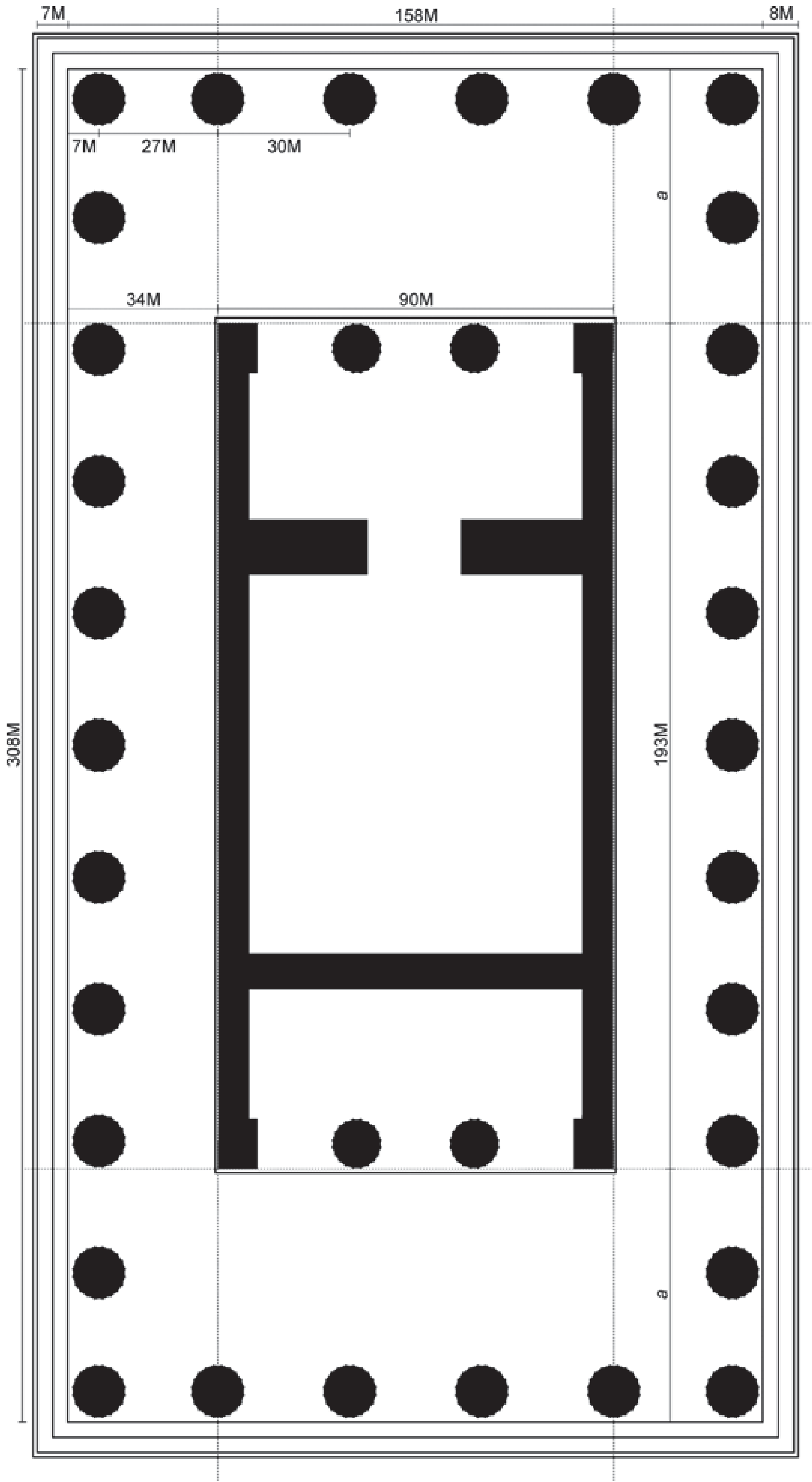


**Fig. 10.** The temple of Zeus at Stratos. Plan with principal dimensions expressed in terms of the design module of 0.1053 m. J.P.

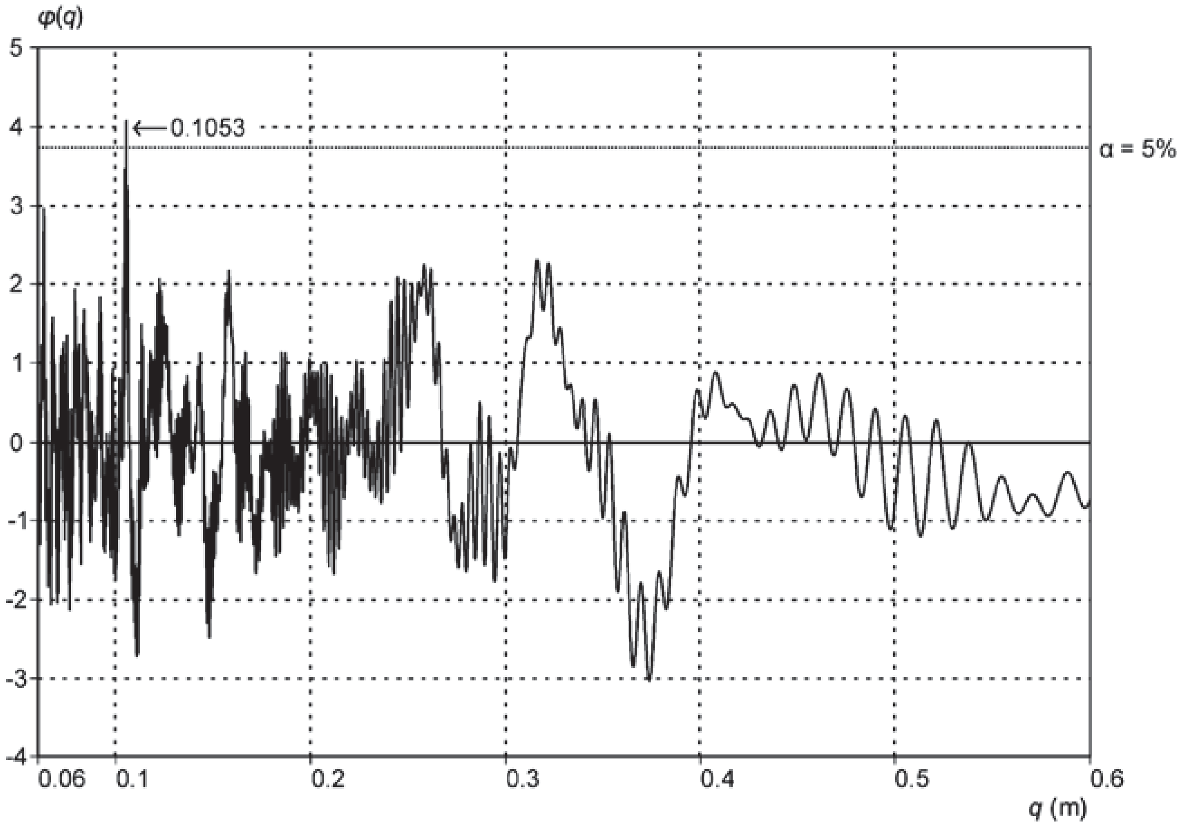


**Fig. 11.** The temple of Zeus at Stratos. Cosine quantogram analysis of facade measurements. J.P.

be observed in Doric ground plans. Using a uniform square grid over the whole plan as in the Ionic is quite impossible: in order to attain a more regular frieze, the corner intercolumniation needs to be contracted in the Doric order.[60] The temple at Stratos comes as close to Ionic simplicity in plan as is possible in a Doric building: the angle contraction is exactly one tenth of the normal axial intercolumniation, and the whole plan follows a strict design principle.

The better fit of the plan dimensions compared to the facade data at Stratos could possibly be explained by the use of a successive design system by the architect. Following Vitruvius' rules for the Ionic order, J. J. Coulton has proposed that the opacity observable in Doric design could be explained by the fact that the building facade does not meticulously follow a modular

[60] See e.g. Coulton (above n. 45) 60–64, 70–71; Wilson Jones (above n. 3) 675–78. Attempts to analyse Doric temple plans as modular have e.g. resorted to trying to define 'original' and 'executed' planning phases; R. de Zwarte, "Der ursprüngliche Entwurf für das Hephaisteion in Athen – Eine modulare architektonische Komposition des 5. Jhs v. Chr.", *BABesch* 71 (1996) 95–102.

system.[61] In Vitruvius the module is derived from the building width, but higher up in the facade this module is quickly abandoned and the sizes of further building elements are derived from the previous parts: the dimensions of the plan are directly related to the design unit, but, for example, the architrave depth is one step and the geison height several steps removed from the initial module. The major discrepancies observable in Table 2 could also be explained by the use of sub-divisions of the module, but their introduction to the analysis would not necessarily increase our knowledge of the general design: for example, the mean capital height of 0.502 m is very close to $4^3/_4$ modules, but one quarter module (c. 26 mm) already falls too close to the above defined error margin of ±10 mm to be necessarily classified as significant.[62] Therefore, the question of whether the design of the Doric temple facades should rather be classified as following a successive proportional system than a strictly modular one cannot definitively be answered on the basis of an analysis of a single building.[63]

There are two equally likely interpretations how the detected design unit of 0.1053 m could be related to a foot unit of 0.316 m: it could either be a specific unit used only in the temple design or one third of a local foot standard. W. Koenigs has suggested that the design unit of a Greek building, the 'Iochmodul', was derived from the intercolumniation of the building and that the sizes of the other elements are related to this module rather than the standard measurement unit otherwise employed in the region.[64] If the

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[61] Vitr. 3,5,1–15; Coulton (above n. 51) 68–74.

[62] In general, the introduction of small sub-divisions of both modules and metrological units into design analyses should be discouraged: they may simply mask any significant patterns by eliminating all real discrepancies.

[63] In Wilson Jones (above n. 3) 675–713 it has been recently suggested that already 5th-century Doric facades are based on a modular design. Besides the criticism put forward above in n. 3, the principal difficulty in Wilson Jones' method is that it largely omits the plan dimensions: Wilson Jones assumes that the size of a possibly used module is linked to the triglyph width but he adjusts this dimension to produce smaller discrepancies in relation to a few facade and plan dimensions. All in all, the method is quite subjective compared to an appropriate statistical approach. In Coulton (above n. 51) 70 a possible research project for detecting modular and proportional relationships in Greek buildings is outlined, though it could be modified to employ a more developed statistical analysis.

[64] Koenigs (above n. 55) 211–26; Coulton argues that a more correct term for Koenig's 'Iochmodul' would be 'Iochfuss'; J. J. Coulton, "Modules and Measurements in Ancient Design and Modern Scholarship" in H. Geertman & J. J. de Jong (eds.), *Munus Non Ingratum. Proceedings of the International Symposium on Vitruvius' De Architectura and*

standard measurement unit at Stratos could be defined as something else than 0.316 m, this would strongly support Koenigs' theory. Discussion of metrological units employed in the Greek world is, however, hampered by the fact that most studies on the topic are methodologically unsound. Therefore, further analyses of Greek architecture and urban planning are needed to solve the question of foot standards in general and the one used at Stratos.

## 6. Conclusions

Based on new fieldwork at the sanctuary of Zeus at Stratos, the height of the temple peristyle column can be established as 7.88–7.93 m. The proportional column height of 6.11–6.15 times the lower diameter is very conservative for an Early Hellenistic building; the great diameter difference between the partially carved top drum and the finished capital suggests that the temple was originally designed with one more drum per column. The change in plans can plausibly be connected with the economic strain the large-scale urban development caused to the polis finances at the end of the fourth century BC. The planned height can be estimated as 8.67–8.73 m, which is 6.72–6.77 times the lower diameter.

The roughly finished exterior columns do not allow for a reconstruction of the final shaft profile, but the porch columns were worked one step further and demonstrate how the entasis was taken into consideration in the final preliminary phase before cutting the fluting could have begun. The shaft displays a gentle curvature with a maximum projection of 13 mm.

Any study which attempts to discover the proportional relationships and metrological units used in Greek architecture must start with a statistical analysis of the building dimensions: this is the only way to assure that all relevant possibilities are taken into account. Cosine quantogram analysis of

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*the Hellenistic and Republican Architecture. Leiden 20–23 January 1987,* Leiden 1989, 87. A foot unit of 0.315 m for the East Stoa of the South Agora at Miletos has been argued by de Waele based on inscriptional and archaeological evidence, but is not clear whether the unit should be classified as a 'Iochfuss' related only to this building or as a regional foot standard; J. A. de Waele, "Der Entwurf des Parthenon", in E. Berger (ed.), *Parthenon-Kongreß Basel. Referate und Berichte 4. bis 8. April 1982,* Mainz 1984, 99–100; cf. Koenigs (above n. 55) 212.

the Stratos data shows that the length of the unit used in the design of building elements is 0.1053 m. The layout of the temple follows nearly in its entirety a strictly modular pattern; the only exception is the lengthwise placement of the cella according to the sides of the flank columns. The fit of the facade dimensions to the design unit, especially the ones of the superstructure above the krepis, is not as good as the plan data: the use of a successive proportional design system where the upper elements are not directly derived from the module could be a possible explanation for this. The length of the design unit suggests that a foot standard of 0.316 m was employed in the temple construction, but its relationship to the local unit at Stratos remains unresolved.

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**Table 1.** The temple of Zeus at Stratos. Principal plan dimensions expressed in terms of the design module of 0.1053 m. Dimensions from Courby & Picard (above n. 6).

| A. | B. Measured dimension (m) | C. Modules | D. Discrep. (m) |
|---|---|---|---|
| Euthynteria width | 18.32 | 174 | –0.002 |
| Building width at first step | 18.11 | 172 | –0.002 |
| Stylobate width | 16.64 | 158 | 0.003 |
| Euthynteria length | 34.12 | 324 | 0.003 |
| Building length at first step | 33.91 | 322 | 0.003 |
| Stylobate length | 32.44 | 308 | 0.008 |
| Axial width of facade | 15.17 | 144 | 0.007 |
| Interaxial distance of columns | 3.16 | 30 | 0.001 |
| Interaxial distance at corner | 2.845 | 27 | 0.002 |
| Distance of column axis from stylobate edge | 0.735 | 7 | –0.002 |
| Stylobate block width | 1.58 | 15 | 0.000 |
| Cella width at toichobate level | 9.59 | 91 | 0.008 |
| Cella width between exterior faces of antae | 9.48 | 90 | 0.003 |
| Cella length at toichobate level | 20.49 | 195 | –0.044 |
| Cella length between exterior faces of antae | 20.325 | 193 | 0.002 |
| Interaxial distance of porch columns | 2.825 | 27 | –0.018 |
| Interaxial distance between anta and pronaos column axes | 2.85 | 27 | 0.007 |

**Table 2.** The temple of Zeus at Stratos. Principal facade dimensions expressed in terms of the design module of 0.1053 m. Dimensions mainly from Courby & Picard (above n. 6); new data printed with bold typeface.

| A. | B. Measured dimension (m) | C. Modules | D. Discrep. (m) |
|---|---|---|---|
| Euthynteria width | 18.32 | 174 | –0.002 |
| Building width at first step | 18.11 | 172 | –0.002 |
| Stylobate width | 16.64 | 158 | 0.003 |
| Axial width of facade | 15.17 | 144 | 0.007 |
| Interaxial distance of columns | 3.16 | 30 | 0.001 |
| Interaxial distance at corner | 2.845 | 27 | 0.002 |
| Distance of column axis from stylobate edge | 0.735 | 7 | –0.002 |
| Stylobate block width | 1.58 | 15 | 0.000 |
| Krepis height | 1.265 | 12 | 0.001 |
| Lower column diameter | **1.29** | 12 | 0.026 |
| Upper column diameter | **1.01** | 10 | –0.043 |
| Abacus width | 1.36 | 13 | –0.009 |
| Capital height | **0.502** | 5 | –0.024 |
| Triglyph width | 0.625 | 6 | –0.007 |
| Metope width | 0.955 | 9 | 0.007 |
| Architrave depth | 1.25 | 12 | –0.014 |
| Architrave height | 0.825 | 8 | –0.017 |
| Frieze height | 0.946 | 9 | –0.002 |
| Geison height | 0.248 | 2 | 0.037 |
| Entablature height | 2.019 | 19 | 0.018 |