

Engineering the Trebuchet

From Ancient Siege Warfare to Optimal Design

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University of Illinois Urbana-Champaign, 16 October 2026

1. Introduction

When Titus besieged Jerusalem in AD 70, the engines of his tenth legion threw stones that “were of the weight of a talent, and were carried two furlongs and further” [1, 5.270]. That is about 26 kg carried at least 370 m. The stones were white, and watchmen on the towers cried “The son cometh” whenever an engine let go [1, 5.271–72]. The ground tells a smaller story. Of 79 stones excavated in front of the city’s outermost wall, most weigh up to 5 kg and one weighs 24 kg [2, pp. 109–10].

Reports like these raise an engineering question. How far could the best possible stone-thrower reach, and could it have broken a city wall? This report puts the question to the trebuchet, the beam-and-sling engine of the Middle Ages. A physics model of the throw, checked against published models and measured reconstructions, is used to design two machines. The Optimal trebuchet may use any material. The Jerusalem 1187 trebuchet may use only what Saladin’s army could have built when it besieged the city in September 1187. Both are compared with machines that people actually built, and the second is set against the wall Saladin attacked.

2. From Traction to Counterweight

The first trebuchets were pulled by people. The type arose in China between the fifth and third centuries BC and reached the eastern Mediterranean by the late sixth century AD [3, pp. 66–67]. A crew hauled down the short end of a pivoting beam so that the long end swung up and whipped a sling [4].

When a falling weight replaced the crew is disputed. George Dennis reads a winch mentioned at Zevgminon in 1165 as the first clear reference to a counterweight machine [5, p. 113]. Michael Fulton places its appearance in the last two decades of the twelfth century, and the earliest known drawing of one is in a treatise dedicated to Saladin, which Fulton dates to 1180 [4]. No source read for this project puts counterweight engines at Jerusalem in 1187, so Saladin’s machines are called mangonels here, as in the translated chronicles.

Weighed stones show what these engines threw. Most of those from the Mamluk siege of Arsuf in 1265 weigh 8 to 48 kg, and the heaviest 78 kg [6, p. 87]. Whether such stones broke walls is debated. Fulton argues that wherever a fortress was taken in the crusading era, it fell by other means, most often mining [4].

3. Method

The model, written in Python for this project, treats a trebuchet as rigid parts joined by pins and derives their equations of motion by Lagrange's method. It covers six layouts: traction, a fixed or hinged counterweight on a fixed or wheeled frame, and the floating arm, whose weight drops straight down in guides while its axle rolls forward on a rail. Friction in each bearing follows the load on it [7, eq. 3], and the stone flies with an assumed drag coefficient of 0.40.

The model reproduces Horsdal's published design for a 19.1 t counterweight to within 0.2% in range and peak axle load [8, table 1]. Real throws are harder. The model puts the field throws of Horsdal's laboratory engine at Aarhus 9 to 17% long [9, table 3], because a rigid model ignores the shifting of the trestle and the bending of the beam [7, Sec. 5.3]. Hansen's reconstruction at Nykøbing threw a 15 kg ball 168 m [10, "The Trials"], where the model, guessing the weight of its beam, gives 180 m. Model ranges are therefore about 10 to 15% optimistic, a bias that every design shares.

Built to the same proportions, Horsdal's scaled engines from 1.2 to 10 m all throw 33.7 times the length of their beam in a vacuum [7, Secs. 6.1, 6.7, table 6]. Each machine is therefore scored, at the same ratio of counterweight to stone, by $R^* = R/(L_1 + L_2)$, its range divided by its beam length (long arm L_1 plus short arm L_2), and by its efficiency η , the share of the counterweight's available energy that leaves with the stone. Strength does not scale, so materials are sized on one reference machine with a 10 m beam, a 20 kg stone, one of the commonest weights at Arsuf [6, p. 87], and a 3,000 kg counterweight, 150 times the stone and between the 133 of Hansen's machine and the 191 of Horsdal's design [8, table 1], [10, "The Trials"].

Each feature was settled by precedent and the model together. Every candidate layout, bearing, timber or sling was re-optimised on its own terms before it was compared, with the beam sized to survive its own throw. The same equations drive an interactive simulator, built with Claude [11], in which every parameter of both designs can be changed.

4. Two Designs

In modern materials the floating arm wins clearly, throwing 885 m against 747 m for the best wheeled machine and 698 m for the best hinged one. It needs steel guides and a rail, so for 1187 the choice lies between a hinged counterweight (579 m) and a fixed weight on a rolling frame (586 m). The rolling frame's small lead rests on a rolling resistance we had to assume, so the 1187 design keeps a hinged weight on a fixed frame.

The beam matters more than any other choice. A uniform ash beam strong enough for its loads weighs 321 kg, and the machine throws 455 m. Tapered from full depth at the axle to half that depth at the tip, the beam weighs 241 kg and the machine throws 580 m, 27% farther, because every kilogram of beam has to be swung up to speed with the stone. In modern materials a carbon-fibre tube of 99 kg does the same work.

No magic ratio comes out of the search. The period optimum sits where four limits meet: the hanger as long as the ground allows, the axle as high as the 0.75 beam lengths we allowed, the hinge pin at the 5 t load we set and the beam at its design stress. Its arm ratio L_1/L_2 is 4.8 and its hanger 2.8 times the short arm, its sling is as long as the long arm, and it starts 26° from the vertical (Figure 1 and Table 1). All but the sling fall within Horsdal's independently optimised designs [9, table 4], [12]. A taller frame would always help, and lowering this one from 7.5 to 5.9 m costs 25% of the range. Range keeps rising with the counterweight, so the ratio of 150 rests on precedent and logistics rather than on a peak.

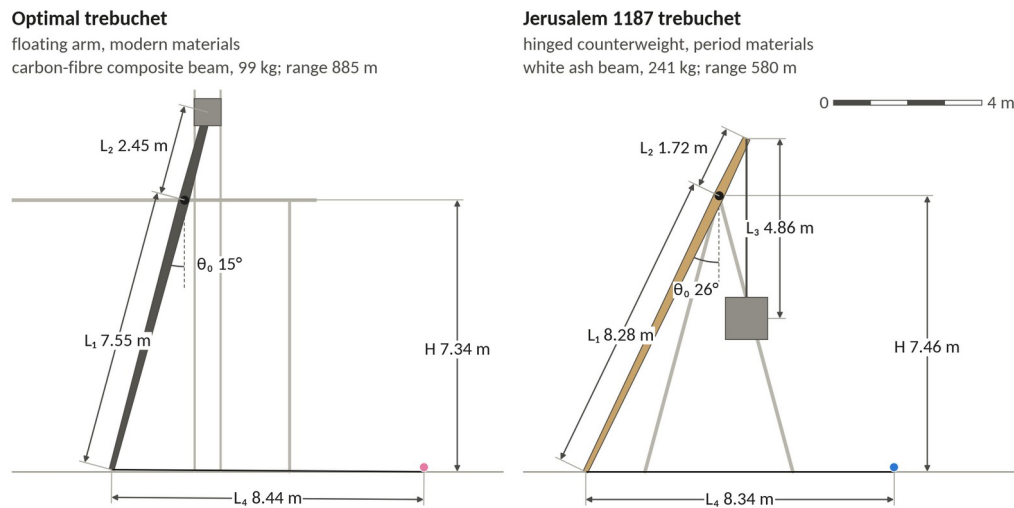


Figure 1. The two designs, drawn to the same scale and cocked for the throw. Both have a 10 m beam and an axle about 7.4 m up. They differ in how the counterweight falls and in what the beam is made of. Image created by Claude [11].

Table 1. The two designs at the reference scale (10 m beam, 20 kg stone). Ranges are model values, about 10 to 15% optimistic.

	Optimal trebuchet	Jerusalem 1187 trebuchet
Layout	Floating arm on a rail	Hinged counterweight, fixed oak frame
Beam	Carbon-fibre tube, tapered, 99 kg	White ash, tapered, 241 kg
Counterweight	3,000 kg in a steel box	3,000 kg of rubble in a timber box
Axle bearings	Rolling bearings	Iron journals in greased hardwood
Sling	8 mm HMPE rope	25 mm hemp rope
Range, R^*	885 m, 88.5	580 m, 58.0
Efficiency η	0.91	0.75
Release	114 m/s at 38°	85 m/s at 40°

With the model's optimism removed, the 1187 design's 580 m is better read as about 500 m, and the floating arm has no measured throw to check it against. A besieger also wanted weight. With the sling and release re-tuned for each stone, the 1187 design throws 4 kg 791 m and 40 kg 340 m. Its 20 kg stone strikes with 47 kJ and the 40 kg stone with 65 kJ, but past

about 40 kg the impact energy barely grows, because the machine can no longer bring a heavier stone up to speed.

5. History against the Optimum

Two reconstructions built to medieval patterns, Hansen's at Nykøbing in Denmark and one at Varbola in Estonia, reached R^* 24 and 16 as reported, only 41% and 28% of the 1187 design's 58.0 [10, "The Trials"], [13, pp. 75–76]. Hansen's machine shows where the gap lies. Scaled to the reference machine, and assuming that its unweighed beam weighed a fifth of the counterweight, it scores 25.8. An ash beam sized to its loads adds 16.4 and raising the axle to the design's height adds 14.3, while re-proportioning the machine for its own frame adds only 1.5. Its arm ratio of 4.9 and hanger of 1.1 short arms [13, p. 75] are close to the 4.7 and 1.0 that suit so low a frame.

Saimre had already pointed to the frame. The axle stood "only 3.15 m" high, and raising it by a metre "would result in an increase of the theoretical maximum range by 17%" [13, p. 75]. Our model gives 18%. The sources do not say why builders kept frames low and beams heavy. Our inference is that a tall frame needs long timbers and stands less steadily, while a heavy beam rarely breaks. Hansen's machine fired about 120 shots and "functioned nearly flawlessly in all of them" [10, "The Trials"].

6. Jerusalem, 1187

Saladin's siege opened on 20 September 1187 on the west, opposite the Tower of David [14, pp. 159–63]. Five days later his mangonels were working against the north-east angle [15, "Salah al-Din's Attack"]. In the Arabic accounts the mangonels destroyed the tops of the towers and drove off the defenders, and in two days the sappers opened a breach about 30 m long [15, "Salah al-Din's Attack"]. The city surrendered on 2 October, twelve days after the siege began [14, pp. 159–63], [15, "The Surrender of Jerusalem"]. None of these accounts gives the size of an engine or the weight of a stone.

On the north the attackers faced a rock-cut moat 14 to 20 m wide and a forewall 3.2 to 4.5 m thick, 8 to 10 m in front of the main wall [16, pp. 424, 425, 436, 443, 445]. The main wall is unmeasured, so we take it as 11 m high and 2.5 m thick, close to the walls Pisa built in the same century [17, Sec. 2]. The defenders' longest shot is taken as the 421 m that Payne-Gallwey reached with a later steel siege crossbow [18, Ch. III, 14–15].

Figure 2 shows what the 1187 design could have done. From 421 m it still throws a 32 kg stone that strikes with 60 kJ, but it mostly misses. Coming down at about 49°, the stone passes the 11 m face in about 10 m of forward travel, and landings scatter by 13 to 16 m, so only 27 to 30% of long shots hit the face. From a stand-off of 70 to 150 m, our judgement since no source gives one, it throws 108 kg to 98 m and hits the face 68% of the time with 68 kJ. A 20 kg stone strikes with 47 kJ, a little more than the 41 kJ implied by Josephus's talent at two stades, but a 20 cm iron cannon ball at 200 m/s carries 660 kJ [17, Sec. 4].

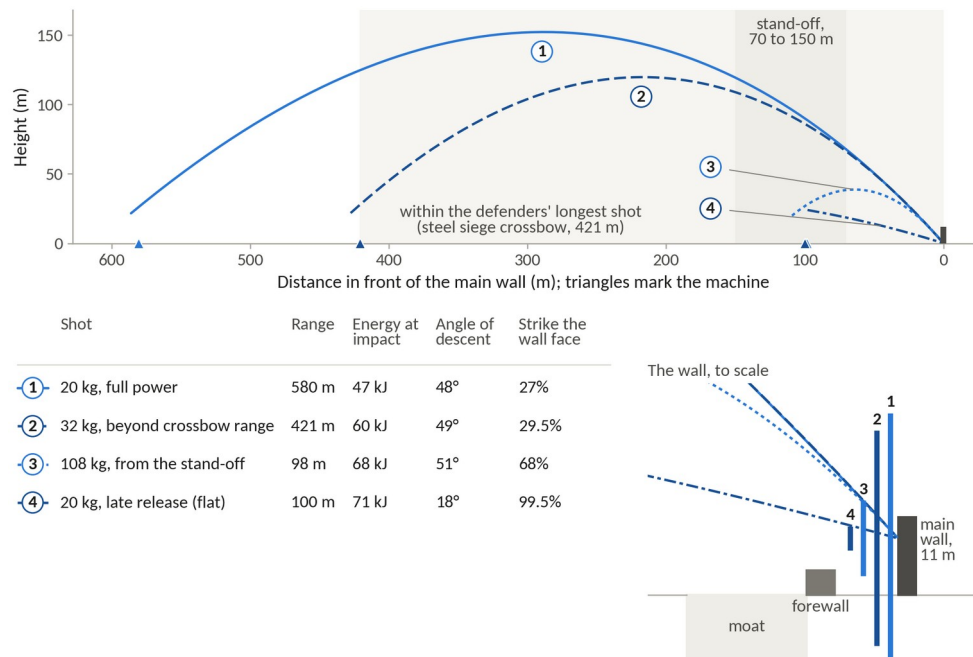


Figure 2. Out of crossbow range the 1187 design mostly misses the wall, and from the stand-off it mostly hits. Above, four flight paths to scale. Below, the four settings and, at right, the wall and its outer defences to scale with each setting's shot-to-shot spread. Shares are from 200 simulated shots per setting, aimed 8 m up the face, without wind. Image created by Claude [11].

The machine would probably not have broken the wall on its own, and not in twelve days. At Hansen's pace of one shot every ten minutes [10], a twelve-hour day at the stand-off puts 50 to 70 stones on the face, each with about a tenth of a cannon ball's energy. It was gunpowder that forced builders to thicken their walls [17, abstract], and nothing suggests such a battering would match the 30 m that the sappers opened in two days. The machine's value would have been to wreck the tower tops from beyond crossbow range and cover the miners. Our confidence is low to medium, because the wall and the stand-off are estimates and no one has tested how impact energy turns into a breach.

7. Conclusions

The best trebuchet that physics and modern materials allow is a floating arm that throws a 20 kg stone 885 m from a 10 m beam in the model. The best that could have been built in 1187 is a tall hinged machine with a tapered ash beam that throws the same stone 580 m, or about 500 m allowing for the model's optimism. Medieval-pattern machines had nearly the right proportions for their frames and lost range to heavy beams and low frames, a trade that suited builders who wanted heavy stones. At Jerusalem the best machine of 1187 would have ruled the top of the wall without breaking it. The sappers would still have made the breach.

References

- [1] Josephus, "The Wars of the Jews," in *The Works of Flavius Josephus*, Auburn: John E. Beardsley, 1895. Accessed: Oct. 01, 2026. [Online]. Available: https://lexundria.com/j_bj/5.270/wst
- [2] K. Arbiv, "Evidence of the Roman Attack on the Third Wall of Jerusalem at the End of the Second Temple Period," *'Atiqot*, vol. 111, pp. 103–118, 2023, doi: 10.70967/2948-040X.1064.
- [3] P. E. Chevedden, L. Eigenbrod, V. Foley, and W. Soedel, "The Trebuchet," *Scientific American*, vol. 273, no. 1, pp. 66–71, Jul. 1995. doi: 10.1038/scientificamerican0795-66.
- [4] P. Purton, "Michael S. Fulton, *Artillery in the Age of the Crusades: Siege Warfare and the Development of Trebuchet Technology*," *De Re Militari*. Nov. 12, 2018. Accessed: Oct. 02, 2026. [Online]. Available: <https://deremilitari.org/2018/11/michael-s-fulton-artillery-in-the-age-of-the-crusades-siege-warfare-and-the-development-of-trebuchet-technology-purton/>
- [5] G. T. Dennis, "Byzantine Heavy Artillery: The Helepolis," *Greek, Roman, and Byzantine Studies*, vol. 39, pp. 99–115, 1998, Accessed: Oct. 02, 2026. [Online]. Available: <https://grbs.library.duke.edu/article/viewFile/2521/6333>
- [6] K. Raphael and Y. Tepper, "The Archaeological Evidence from the Mamluk Siege of Arsūf," *Mamlūk Studies Review*, vol. 9, no. 1, pp. 85–100, 2005, Accessed: Oct. 02, 2026. [Online]. Available: https://knowledge.uchicago.edu/record/1062/files/MSR_IX-1_2005-Raphael-Tepper_17MB.pdf
- [7] E. Horsdal, "The Swinging Counterweight Trebuchet: On Internal Friction," Preprint, arXiv, Oct. 23, 2025. doi: 10.48550/arXiv.2510.21869.
- [8] E. Horsdal, "The Swinging Counterweight Trebuchet: On Internal Forces," Preprint, arXiv, Oct. 21, 2025. doi: 10.48550/arXiv.2510.18789.
- [9] E. Horsdal, F. D. Johansen, and J. Rasmussen, "The Swinging Counterweight Trebuchet: Experiments on Inner Movement and Ranges," Preprint, arXiv, Feb. 24, 2025. doi: 10.48550/arXiv.2502.19442.
- [10] P. V. Hansen, "Experimental Reconstruction of a Medieval Trébuchet," *Acta Archaeologica*, vol. 63, pp. 189–268, 1992, Accessed: Oct. 02, 2026. [Online]. Available: https://linnamuseum.ee/JaanMarss/juhendid/Mehaanilised_kaugrelvad_keskajal/andmebaas/Middelaldercentret/Peter%20Vemming%20Hansen/acta.html
- [11] Anthropic, "Claude (model claude-opus-5-5), large language model." Accessed: Oct. 10, 2026. [Online]. Available: <https://claude.ai>
- [12] E. Horsdal, "The Swinging Counterweight Trebuchet: On Scaling and Optimization," Preprint, arXiv, Mar. 01, 2023. doi: 10.48550/arXiv.2303.01306.
- [13] T. Saimre, "Trebuchet – A Gravity-Operated Siege Engine: A Study in Experimental Archaeology," *Estonian Journal of Archaeology*, vol. 10, no. 1, pp. 61–80, 2006, doi: 10.3176/arch.2006.1.03.
- [14] J. A. Brundage, Trans., "De expugnatione Terrae Sanctae per Saladinum," in *The Crusades: A Documentary Survey*, Milwaukee: Marquette University Press, 1962, pp. 159–163. Accessed: Oct. 01, 2026. [Online]. Available: <https://www.fordham.edu/halsall/source/1187saladin.asp>
- [15] H. Dajani-Shakeel, "Some Medieval Accounts of Salah al-Din's Recovery of Jerusalem (Al-Quds)," in *Studia Palaestina: Studies in Honour of Constantine K. Zurayk*, H. Nashabe, Ed., Beirut: Institute for Palestine Studies, 1988. Accessed: Oct. 01, 2026. [Online]. Available: <https://sourcebooks.web.fordham.edu/med/salahdin.asp>
- [16] S. Weksler-Bdolah, "Early Islamic and Medieval City Walls of Jerusalem in Light of New Discoveries," in *Unearthing Jerusalem: 150 Years of Archaeological Research in the Holy City*, K. Galor and G. Avni, Eds., Winona Lake, IN: Eisenbrauns, 2011, pp. 417–447. Accessed: Oct. 01, 2026. [Online]. Available: <https://www.academia.edu/6858175>
- [17] V. Tateo and S. Casolo, "Explicit Dynamic Analysis by a Rigid Body-Spring Model of Impact Loads of Artillery on Middle Age Fortifications," *Buildings*, vol. 11, no. 12, p. 607, 2021, doi: 10.3390/buildings11120607.
- [18] R. Payne-Galloway, *The Book of the Crossbow*. New York: Dover Publications, 1995. Accessed: Oct. 02, 2026. [Online]. Available: https://archive.org/stream/Book_of_the_Crossbow_The_by_Sir_Ralph_Payne-Galloway/Book_of_the_Crossbow_The_by_Sir_Ralph_Payne-Galloway_djvu.txt