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ON THE

PRINCIPLES OF CONSTRUCTION

IN THE CARPENTRY AND JOINERY

OF

ROOFS.

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THIRTY-FOUR ILLUSTRATIVE DIAGRAMS.

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1859.

CONTENTS.

THIRTY-FOUR WOOD-CUTS.

ON THE

CONSTRUCTION OF ROOFS.

1. THE word Roof expresses the covering of a house or building, by which its inhabitants or contents are protected from the injuries of the weather. A roof is not only an essential part of a house, but it even seems to be its characteristic feature; as, for example, the roofs of palatial, public, and private buildings in France, which are denominated the Mansard Roof, and more essentially the picturesque roofs of the ancient Châteaux of France.* The upper structures of houses in Turin have a most picturesque effect,† and not so much in England (although many interesting examples still exist) as we might desire to see.

The Greeks, who have perhaps excelled all nations in taste, and who have given the most perfect model of architectonic ordonnance within a certain limit, never

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* Petit's most interesting examples, both 4to. and folio. *Weale.*

† For Photographic Examples from Turin, see *Weale's Catalogue*, under "Italian Architecture."

erected a building which did not exhibit the roof in the distinctest manner; and though they borrowed much of their model from the Orientals, as will be evident to any one who compares their architecture with the ruins of Persepolis, and of the tombs in the mountains of Shiraz, they added that form of roof which their own climate taught them was necessary for sheltering them from the rains. The roofs in Persia and Arabia are flat, but those of Greece are, without exception, sloping. It seems, therefore, a gross violation of the principles of taste in architecture, to take away or hide the roof of a house; and it must be ascribed to that rage for novelty which is so powerful in the minds of the rich. Our ancestors seemed to be of a very different opinion, and turned their attention to the ornamenting of their roofs as much as any other part of the building. They showed them in the most conspicuous manner, running them up to a great height, broke them into a thousand fanciful shapes, and stuck them full of highly dressed windows. We laugh at this, and call it Gothic and clumsy; and our great architects conceal the roof altogether by parapets, balustrades, and other contrivances. Our forefathers certainly did offend against the maxims of true taste, when they enriched a part of a house with marks of elegant habitation, which every spectator must know to be a cumbersome garret: but their successors no less offend, who take off the cover of the house altogether, and make it impossible to know whether it is not a mere screen or colonnade we are looking at.

2. We cannot help thinking that Sir Christopher Wren erred when he so industriously concealed the roof of St. Paul's cathedral, London. The whole of the upper order is a mere screen. Such a quantity of wall would have been intolerably offensive, had he not given it some appearance of habitation by the mock windows or niches. Even in this state it is gloomy, and it is odd, and is a puzzle to every spectator.—There should be no puzzle in the design of a building any more than in a discourse. It has been said that the double roof of our great churches which have aisles is an incongruity, looking like a house standing on the top of another house. But there is not the least occasion for such a thought. We know that the aisle is a shed, a cloister. Suppose only that the lower roof or shed is hidden by a balustrade, it then becomes a portico, against which the connoisseur has no objection: yet there is no difference; for the portico must have a cover, otherwise it is neither a shed, cloister, nor portico, any more than a building without a roof is a house. A house without a visible roof is like a man abroad without his hat; and we may add, that the whim of concealing the chimnies, once so fashionable, changes a house to a barn or storehouse. A house should not be a copy of any thing. It has a title to be an original; and a screen-like house and a pillar-like candlestick are similar solecisms in taste.

3. The architect is anxious to present a fine object, and a very simple outline dismisses all his concerns with the roof. He leaves it to the carpenter, whom he frequently puzzles (by his arrangements) with coverings almost impossible to execute. Indeed it is seldom that the idea of a roof is admitted by him into his great compositions; or if he does introduce it, it is from mere affectation, and we may say, pedantry. A pediment is frequently stuck up in the middle of a grand front, in a situation where a roof cannot perform its office; for the rain that is supposed to flow down its sides must be received on the top of the level buildings which flank it. This is a manifest incongruity. The tops of dressed windows, trifling porches, and sometimes a projecting portico, are the only situations in which we see the figure of a roof correspond with its office. Having thus lost sight of the principle, it is not surprising that the draughtsman (for he should not be called architect) runs into every whim: and we see pediment within pediment, a round pediment, a hollow pediment, and the greatest of all absurdities, a broken pediment. Nothing could ever reconcile us to the sight of a man with a hat without its crown, because we cannot overlook the use of a hat.

4. But when one builds a house, ornament alone will not do. We must have a cover: and the enormous expense and other great inconveniences which attend the concealment of this cover by parapets, balustrades, and screens, have obliged architects to consider the

pent roof as admissible, and to regulate its form. Any man of sense, not under the influence of prejudice, would be determined in this by its fitness for answering its purpose. A high pitched roof will undoubtedly shoot off the rains and snows better than one of a lower pitch. The wind will not so easily blow the dropping rain in between the slates, nor will it have so much power to strip them off. A high pitched roof will exert a smaller thrust on the walls, both because its strain is less horizontal, and because it will admit of lighter covering. But it is more expensive, because there is more of it. It requires a greater size of timbers to make it equally strong, and it exposes a greater surface to the wind.

5. There have been great changes in the pitch of roofs: our forefathers made them very high, and we make them very low. It does not, however, appear, that this change has been altogether the effect of principle. In the simple unadorned habitations of private persons, everything comes to be adjusted by an experience of inconveniences which have resulted from too low pitched roofs; and their pitch will always be nearly such as suits the climate and covering. Our architects, however, go to work on different principles. Their professed aim is to make a beautiful object. The sources of the pleasures arising from what we call *taste* are so various, so complicated, and even so whimsical, that it is almost in vain to look for principle in the rules adopted by our professed architects. We

cannot help thinking that much of their practice results from a *pedantic* veneration for the beautiful productions of Grecian architecture. Such architects as have written on the principles of the art in respect of proportions, or what they call the ORDONNANCE, are very much puzzled to make a chain of reasoning; and the most that they have made of the Greek architecture is, that it exhibits a nice adjustment of strength and strain. But when we consider the extent of this adjustment, we find that it is wonderfully limited. The whole of it consists of a basement, a column, and an entablature; and the entablature, it is true, exhibits something of a connection with the framework and roof of a wooden building; and we believe that it really originated from this in the hands of the orientals, from whom the Greeks certainly borrowed their forms and their combinations. We could easily show in the ruins of Persepolis, and among the tombs in the mountains (which were long prior to the Greek architecture), the fluted column, the base, the Ionic and Corinthian capital, and the Doric arrangement of lintels, beams, and rafters, all derived from unquestionable principle. The only addition made by the Greeks was the pent roof; and the changes made by them in the subordinate forms of things, are such as we should expect from their exquisite judgment of beauty.

But the whole of this is very limited; and the Greeks, after making the roof a chief feature of a house, went no farther, and contented themselves with giving it a slope suited to their climate. This we have followed, because in the milder parts of Europe we have no cogent reason for deviating from it; and if any architect should deviate greatly in a building where the outline is exhibited as beautiful, we should be disgusted; but the disgust, though felt by almost every spectator, has its origin in nothing but habit. In the professed architect or man of education, the disgust arises from pedantry: for there is not such a close connection between the form and uses of a roof as shall give precise determinations; and the mere form is a matter of indifference.

6. We should not therefore reprobate the high-pitched roofs of our ancestors, particularly on the continent. It is there where we see them in all the extremity of the fashion, and the taste is by no means exploded as it is with us. A baronial castle in Germany and France is seldom rebuilt in the pure Greek style, or even like the modern houses in Britain; the high-pitched roofs are retained. We should not call them Gothic, and ugly because Gothic, till we show their principle to be false or tasteless. Now we apprehend that it will be found quite the reverse; and that though we cannot bring ourselves to think them beautiful, we ought to think them so. The construction of the Greek architecture is a transference of the practices that are necessary in a wooden building to a building of stone. To this the Greeks have

adhered, in spite of innumerable difficulties. Their marble quarries, however, put it in their power to retain the proportions which habit had rendered agreeable. But it is next to impossible to adhere to these proportions with freestone or brick, when the order is of magnificent dimensions. Sir Christopher Wren saw this: for his mechanical knowledge was equal to his taste. He composed the front of St. Paul's cathedral, London, of two orders, and he coupled his columns; and still the lintels which form the architrave are of such length that they could carry no additional weight, and he was obliged to truss them behind. Had he made but one order, the architrave could not have carried its own weight. It is impossible to execute a Doric entablature of this size in brick. It is attempted in a very noble front, the Academy of Arts in St. Petersburgh. But the architect was obliged to make the mutules, and other projecting members of the cornice, of granite, and many of them broke down by their own weight.*

7. Here is surely an error in principle. Since stone is the chief material of our buildings, ought not the members of ornamental architecture to be refinements on the essential and unaffected parts of a simple stone-building? There is almost as much propriety in the architecture of India, where a dome is made in

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* Recently the same failure has been exemplified in building the "Colosseum," Regent's Park.

imitation of a lily or other flower inverted, as in the Greek imitation of a wooden building. The principles of masonry, and not of carpentry, should be seen in our architecture, if we would have it according to the rules of just taste. Now we affirm that this is the characteristic feature of what is called the Gothic architecture. In this no dependence is had on the transverse strength of stone. No lintels are to be seen; no extravagant projections. Every stone is pressed to its neighbours, and none is exposed to a transverse strain. The Greeks were enabled to execute their colossal buildings only by using immense blocks of the hardest materials. The Gothic mason could raise a building to the skies without using a stone which a labourer could not carry to the top on his back. Their architects studied the principles of equilibrium; and, having attained a wonderful knowledge of it, they indulged themselves in exhibiting remarkable instances. We call this false taste, and say that the appearance of insecurity is the greatest fault. But this is owing to our habits: our thoughts may be said to run in a wooden train, and certain simple maxims of carpentry are familiar to our imagination; and in the careful adherence to these consists the beauty and symmetry of the Greek architecture. Had we been as much habituated to the equilibrium of pressure, this apparent insecurity would not have met our eye: we would have perceived the strength, and we should have relished the ingenuity.

8. The Gothic architecture is perhaps entitled to the name of rational architecture;* and its beauty is founded on the characteristic distinction of our species. It deserves cultivation: let us examine with attention the nice disposition of the groins and spandrels; let us study the tracery and knots, not as ornaments, but as useful members; let us observe how they have made their walls like honey-combs, and admire their ingenuity as we pretend to admire the instinct infused by the great architect into the bee. All this cannot be understood without mechanical knowledge; a thing which few of our professional architects have any share of. Thus would architectonic taste be a mark of skill; and the person who presents the design of a building would know how to execute it, without committing it entirely to the mason and carpenter.

These observations are not a digression from our subject. The same principles of mutual pressure and equilibrium have a place in roofs and many wooden edifices; and if they had been as much studied as the Normans and Saracens seem to have studied such of them as were applicable to their purposes, we might have produced wooden buildings as far superior to what we are familiarly acquainted with, as the bold and wonderful churches still remaining in Europe are

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* Kallenbach, *Chronologie der Deutsch Mittelalter lichen Baukunst*, 4to., *Munchen*, an admirable work in large 4to., with 84 large plates of examples, both ecclesiastical and domestic.

superior to the timid productions of our stone architecture.*

9. The Norman architects frequently roofed with stone. Their wooden roofs were in general very simple, and their professed aim was to dispense with them altogether. Fond of their own science, they copied nothing from a wooden building, and ran into a similar fault with the ancient Greeks. The parts of their buildings which were necessarily of timber, were made to imitate stone buildings; and Gothic ornament consists in cramming everything full of arches and spandrels. Nothing else is to be seen in their timber works, nay, even in their sculpture.

10. But there appears to have been a rivalship in old times between the masons and the carpenters. Many of the baronial halls are of prodigious width, and are roofed with timber: and the carpenters appeared to have borrowed much knowledge from the masons of those times, and their wide roofs are frequently constructed with great ingenuity. Their aim, like the masons, was to throw a roof over a very wide building without employing great logs of timber.† We have seen roofs 60 feet wide, without having a piece of timber in them above 10 feet long, and 4 inches square. The Parliament House and Tron

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* Bury's *Remains of Ecclesiastical Woodwork.* 4to. London, 1847.

† Brandon's *Open Timber Roofs of the Middle Ages.* London, 1849.

Church of Edinburgh, the great hall of Tarnaway Castle, near Elgin, are specimens of those roofs. They are very numerous on the continent. England still retains a few monuments of private magnificence. Aristocratic state is still great with us; the rancour of our civil wars gave many of the performances of the carpenter to the flames. Westminster Hall exhibits a specimen of the splendid but peculiar taste of the Gothic roofs. It contains essential parts, very properly disposed; but they are hidden with what is conceived to be ornamental; and this is an imitation of stone arches, crammed in between slender pillars which hang down from the principal frames, trusses, or rafters. In a pure Gothic roof, such as Tarnaway Hall, the essential parts are exhibited as things understood, and therefore relished. They are refined and ornamented; and it is here that the inferior kind of taste or the want of it may appear. And here we do not mean to defend all the whims of our ancestors; but we assert that it is no more necessary to consider the members of a roof as a thing to be concealed, than the members of a ceiling, which form the most beautiful part of the Greek architecture. Should it be said that a roof is only a thing to keep off the rain, it may be answered, that a ceiling is only to keep off the dust, or the floor to be trodden under foot, and that we should have neither compartments in the one, nor inlaid work or carpets on the other. The structure of a roof may therefore be exhibited with propriety, and made an ornamental feature. This has been done even in Italy. The Church of St. Maria Maggiore in Rome, and several others are specimens: but it must be acknowledged, that the forms of the principal frames of these roofs, which resemble those of our modern buildings, are very unfit for agreeable ornament. As we have already observed, our imaginations have not been made sufficiently familiar with the principles, and we are rather alarmed than pleased with the appearance of the immense logs of timber which form the couples of these roofs, and hang over our heads with every appearance of weight and danger. It is quite otherwise with the ingenious roofs of the German and Norman architects. Slender timbers, interlaced with great symmetry, and thrown by necessity into figures which are naturally pretty, form altogether an object which no carpenter can view without pleasure. And why should the gentleman refuse himself the same pleasure of beholding scientific ingenuity?

11. The roof is in fact the part of the building which requires the greatest degree of skill, and where science will be of more service than in any other part. The architect seldom knows much of the matter, and leaves the task to the carpenter. The carpenter considers the framing of a great roof as the touchstone of his art; and nothing, indeed, tends so much to show his judgment and his fertility of resource.

12. It must therefore be very acceptable to the student to have a clear view of the principles by which

this difficult problem may be solved in the best manner, so that the roof may have all the strength and security that can be wished for, without an extravagant expense of timber and iron. We have said that mechanical science can give great assistance in this matter. We may add that the framing of carpentry, whether for roofs, floors, or any other purpose, affords one of the most elegant and most satisfactory applications which can be made of mechanical science to the arts of common life. Unfortunately the practical builder is seldom possessed even of the small portion of science which would almost insure his practice from all risk of failure; and, of late date, even our most experienced carpenters have seldom any more knowledge than what arises from their experience and natural sagacity. The most approved authors in our language are Tredgold and Price; De l'Orme and Mathurin Jousse are in like manner the authors most in repute in France. It is not uncommon to see the works of carpenters of the greatest reputation tumble down, in consequence of mistakes from which the most elementary knowledge, to be found in such works as Tredgold's, would have saved them.

13. We shall attempt, in this article, to give an account of the leading principles of this art, in a manner so familiar and palpable, that any person who knows the common properties of the lever, and the composition of motion, shall so far understand them as to be able, on every occasion, so to dispose his materials, with respect to the strains to which they are to be

exposed, that he shall always know the effective strain on every piece, and shall, in most cases, be able to make the disposition such as to derive the greatest possible advantage from the materials which he employs.

14. It is evident that the whole must depend on the principles which regulate the strength of the materials, relative to the manner in which this strength is exerted, and the manner in which the strain is laid on the piece of matter. With respect to the first, this is not the proper place for considering it, and we must refer the reader to Tredgold's *Carpentry*, London, 4to., 1853; Barlow *On the Strength of Materials*, London, 8vo., 1851; Robison's *System of Mechanical Philosophy*, vol. i., "On the Strength of Materials," Edinburgh, 1822.

The force with which the materials of our edifices, roofs, floors, machines, and framings of every kind, resist being broken or crushed, or pulled asunder, is, immediately or ultimately, the cohesion of their particles. When a weight hangs by a rope, it tends either immediately to break all the fibres, overcoming the cohesion among the particles of each, or it tends to pull one parcel of them from among the rest, with which they are joined. This union of the fibres is brought about by some kind of gluten, or by twisting, which causes them to bind each other so hard, that any one will break rather than come out, so much is it withheld by friction. The ultimate resistance is therefore the cohesion of the fibre; the force or strength of all fibrous materials, such as timber, is exerted in much the same manner.* The fibres are either broken or pulled out from among the rest. Metals, stone, glass, and the like, resist being pulled asunder by the simple cohesion of their parts.

The force which is necessary for breaking a rope or wire is a proper measure of its strength. In like manner, the force necessary for tearing directly asunder any rod of wood or metal, breaking all its fibres, or tearing them from among each other, is a proper measure of the united strength of all these fibres. And it is the simplest strain to which they can be exposed, being just equal to the sum of the forces necessary for breaking or disengaging each fibre. And, if the body is not of a fibrous structure, which is the case with metals, stones, glass, and many other substances, this force is still equal to the simple sum of the cohesive forces of each particle which is separated by the fracture. Let us distinguish this mode of exertion of the cohesion of the body by the name of its ABSOLUTE STRENGTH.

When solid bodies are, on the contrary, exposed to great compression, they can resist only to a certain degree. A piece of clay or lead will be squeezed out; a piece of freestone will be crushed to powder; a beam of wood will be crippled, swelling out in the middle, and its fibres loose their mutual cohesion, after which it is easily crushed by the load. A notion may be formed

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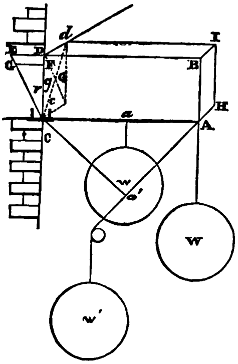
* John Hill on the *Construction of Timber,* folio 1774.

of the manner in which these strains are resisted by conceiving a cylindrical pipe filled with small shot, well shaken together, so that each spherule is lying in the closest manner possible, that is, in contact with six others in the same vertical plane (this being the position in which the shot will take the least room). Thus each touches the rest in six points. Now suppose them all united, in these six points only, by some cement. This assemblage will stick together and form a cylindrical pillar, which may be taken out of its mould. Suppose this pillar standing upright, and loaded above. The supports arising from the cement act obliquely, and the load tends either to force them asunder laterally, or to make them slide on each other: either of these things happening, the whole is crushed to pieces. The resistance of fibrous materials to such a strain is a little more intricate, but may be explained in a way very similar.

A piece of matter of any kind may also be destroyed by wrenching or twisting it. We can easily form a notion of its resistance to this kind of strain, by considering what would happen to the cylinder of small shot if treated in this way.

And lastly, a beam, or a bar of metal, or a piece of stone or other matter, may be broken transversely. This will happen to a rafter or joist supported at the ends when overloaded, or to a beam having one end stuck fast in a wall and a load laid on its projecting part. This is the strain to which materials are most commonly exposed in roofs; and, unfortunately, it is the strain which they are the least able to bear; or rather it is the manner of application which causes an external force to excite the greatest possible immediate strain on the particles. It is against this that the carpenter must chiefly guard, avoiding it when in his power, and, in every case, diminishing it as much as possible. It is necessary to give the reader a clear notion of the great weakness of materials in relation to this transverse strain. But we shall do nothing more, referring him to the works on the STRENGTH OF MATERIALS.

FIG. 1.



15 Let ACDB, Fig. 1. represent the side of a beam projecting horizontally from a wall in which it is firmly fixed, and let it be loaded with a weight W appended to its extremity. This tends to break it; and the least reflection will convince any person that if the beam is equally strong throughout, it will break in the line

CD, even with the surface of the wall. It will open at D, while C will serve as a sort of joint, round which it will turn. The cross section through the line CD is, for this reason, called the *section of fracture*, and the horizontal line, drawn through C on its under surface, is called the *axis of fracture.* The fracture is made by tearing asunder the fibres, such as DE or FG. Let us suppose a real joint at C, and that the beam is really sawed through along CD, and that in place of its natural fibres threads are substituted all over the section of fracture. The weight now tends to break these threads; and it is our business to find the force necessary for this purpose.

It is evident that DCA may be considered as a bended lever, of which C is the fulcrum. If f be the force which will just balance the cohesion of a thread when hung on it so that the smallest addition will break it, we may find the weight which will be sufficient for this purpose when hung on at A, by saying, $AC : CD = f : \phi$, and ϕ will be the weight which will just break the thread, by hanging ϕ by the point A. This gives us $\phi = f \times \frac{CD}{CA}$. If the weight be hung on at a, the force just sufficient for breaking the same thread will be $= f \times \frac{CD}{Ca}$. In like manner the force ϕ, which must be hung on at A in order to break an equally strong or an equally resisting fibre at F, must be $= f \times \frac{CF}{CA}$. And so on all the rest.

If we suppose all the fibres to exert equal resistances at the instant of fracture, we know, from the simplest elements of mechanics, that the resistance of all the particles in the line CD, each acting equally in its own place, is the same as if all the individual resistances were united in the middle point g. Now this total resistance is the resistance or strength f of each particle, multiplied by the number of particles. This number may be expressed by the line CD, because we have no reason to suppose that they are at unequal distances. Therefore, in comparing different sections together, the number of particles in each are as the sections themselves. Therefore DC may represent the number of particles in the line DC. Let us call this line the depth of the beam, and express it by the symbol d. And since we are at present treating of roofs whose rafters and other parts are commonly of uniform breadth, let us call AH or BI the breadth of the beam, and express it by b, and let CA be called its length, l. We may now express the strength of the whole line CD by $f \times d$, and we may suppose it all concentrated in the middle point g. Its mechanical energy, therefore, by which it resists the energy of the weight w, applied at the distance l, is $f.$ CD. Cg, while the momentum of w is $w.$ CA. We must therefore have $f.$ CD. C$g.$ $= w.$ CA, or $f\ d.\ \frac{1}{2}\,d = w.\ l$, and $f\ d : w = l : \frac{1}{2}\,d$, or $f\ d : w = 2\ l : d$. That is, twice the length of the beam is to its depth as the absolute strength of one of its vertical planes to its relative strength, or its power of resisting this transverse fracture.

It is evident, that what has been now demonstrated of the resistance exerted in the line CD, is equally true of every line parallel to CD in the thickness or breadth of the beam. The absolute strength of the whole section of fracture is properly represented by $f. d. b$, and we still have $2\,l : d = f\,d\,b : w$; or twice the length of the beam is to its depth as the absolute strength to the relative strength. Suppose the beam 12 feet long and one foot deep; then whatever is its absolute strength, the 24th part of this will break it if hung at its extremity.

But even this is too favourable a statement; all the fibres are supposed to resist alike in the instant of fracture. But this is not true. At the instant that the fibre at D breaks, it is stretched to the utmost, and is exerting its whole force. But at this instant the fibre at g is not so much stretched, and it is not then exerting its utmost force. If we suppose the extension of the fibres to be as their distance from C, and the actual exertion of each to be as their extensions, it may easily be shown that the whole resistance is the same as if the full force of all the fibres were united at a point r distant from C by two-thirds of CD. In this case we must say, that the absolute strength is to the relative strength as three times the length to the depth; so that the beam is weaker than by the former statement in the proportion of two to three.

Even this is more strength than experiment justifies; and we can see an evident reason for it. When the beam is strained, not only are the upper fibres stretched, but the lower fibres are compressed. This is very distinctly seen, if we attempt to break a piece of cork cut into the shape of a beam: this being the case, C is not the centre of fracture. There is some point *c* which lies between the fibres which are stretched and those that are compressed. This fibre is neither stretched nor squeezed; and this point is the real centre of fracture: and the lever by which* a fibre D resists, is not DC, but a shorter one D *c*; and the energy of the whole resistances must be less than by the second statement. Till we know the proportion between the dilatability and compressibility of the parts, and the relation between the dilatations of the fibres and the resistances which they exert in this state of dilatation, we cannot positively say where the point *c* is situated, nor what is the sum of the actual resistances, or the point where their action may be supposed concentrated. The firmer woods, such as oak and chesnut, may be supposed to be but slightly compressible; we know that willow and other soft woods are very compressible. These last must therefore be weaker: for it is evident, that the fibres which are in a state of compression do not resist the fracture.

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* Robison's *Mechanical Philosophy*, vol. i. "Strength of Materials," p. 440.

It is well known, that a beam of willow may be cut through from C to *g* without weakening it in the least, if the cut be filled up by a wedge of hard wood stuck in.

We can only say, that very sound oak and red fir have the centre of effort so situated, that the absolute strength is to the relative strength in a proportion not less than that of three and a half times the length of the beam to its depth.* A square inch of sound oak will carry about 8000 pounds. If this bar be firmly fixed in a wall, and project about 12 inches, and be loaded at the extremity with 200 pounds it will be broken. It will just bear 190, its relative strength being $\frac{1}{42}$ of its absolute strength; and this is the case only with the finest pieces, so placed that their annual plates or layers are in a vertical position. A larger log is not so strong transversely, because its plates lie in various directions round the heart.

16. These observations are enough to give us a distinct notion of the vast diminution of the strength of timber when the strain is across it: and we see the justice of the maxim which we inculcated, that the carpenter, in framing roofs, should avoid as much as possible the exposing his timbers to transverse strains.† But this cannot be avoided in all cases. Nay, the

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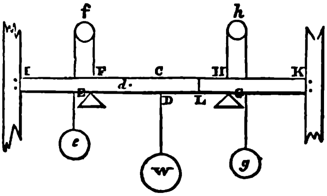
* Robison's *Mechanical Philosophy*, vol i., p. 482.

† Tredgold's *Carpentry*, 4to.; Barlow's *Strength of Materials*, 8vo.

ultimate strain, arising from the very nature of a roof, is transverse. The rafters must carry their own weight, and this tends to break them across: an oak beam a foot deep will not carry its own weight if it project more than 60 feet. Besides this, the rafters must carry the lead, tyling, or slates. We must therefore consider this transverse strain a little more particularly, so far as to know what strain will be laid on any part by any unavoidable load, laid on either at that or at any other.

17. We have hitherto supposed, that the beam had one of its ends fixed in a wall, and that it was loaded at the other end. This is not an usual arrangement, and was taken merely as affording a simple application of the mechanical principles. It is much more usual to have the beam supported at the ends, and loaded in the middle. Let the beam FEGH (Fig. 2) rest on the props E and G, and be loaded at its middle point C with a weight W. It is required to determine the strain at the section CD? It is plain that the beam will receive the same support, and suffer the same

Fig. 2.



strain, if, instead of the blocks E and G, we substitute the ropes E *f* *e*, G *h* *g*, going over the pulleys *f* and *g*, and loaded with proper weights *e* and *g*. The weight *e* is equal to the support given by the block E; and *g* is equal to the support given by G. The sum of *e* and *g* is equal to W; and, on whatever point W is hung, the weights *e* and *g* are to W in the proportion of DG and DE to GE. Now, in this state of things, it appears that the strain on the section CD arises immediately from the upward action of the ropes F *f* and H *h*, or the upward pressions of the blocks E and G; and that the office of the weight W is to oblige the beam to oppose this strain. Things are in the same state in respect of strain as if a block were substituted at D for the weight W, and the weights *e* and *g* were hung on at E and G; only the directions will be opposite. The beam tends to break in the section CD, because the ropes pull it upwards at E and G, while a weight W holds it down at C. It tends to open at D, and C becomes the centre of fracture. The strain therefore is the same as if the half ED were fixed in the wall, and a weight equal to *g*, that is, to the half of W, were hung on at G.*

Hence we conclude, that a beam supported at both ends, but not fixed there, and loaded in the middle, will carry *four times* as much weight as it can carry at its extremity, when the other extremity is fast in a wall.

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* Gregory's *Mathematics for Practical Men*, 8vo., London 1848, p. 372.

The strain occasioned at any point L by a weight W, hung on at any other point D, is $= W \times \frac{DE}{EG} \times LG$. For EG is to ED as W is to the pressure occasioned at G. This would be balanced by some weight *g* acting over the pulley *h*; and this tends to break the beam at L, by acting on the lever GL. The pressure at G is $W. \frac{DE}{EG}$, and therefore the strain at L is $W. \frac{DE}{EG}. LG$.

In like manner, the strain occasioned at the point D by the weight W hung on there, is $W \times \frac{DE}{EG} \times DG$; which is therefore equal to $\frac{1}{2}$ W, when D is the middle point.

Hence we see, that the general strain on the beam arising from one weight, is proportionable to the rectangle of the parts of the beam, (for $\frac{W.DE.DG}{EG}$ is as DE.DG), and is greatest when the load is laid on the middle of the beam.

We also see, that the strain at L, by a load at D, is equal to the strain at D by the same load at L. And the strain at L, from a load at D, is to the strain by the same load at L as DE to LE. These are all very obvious corollaries; and they sufficiently inform us concerning the strains which are produced on any part of the timber by a load laid on any other part.

If we now suppose the beam to be fixed at the two ends, that is, firmly framed, or held down by blocks at I and K, placed beyond E and G, or framed into posts, it will carry twice as much as when its ends were free. For suppose it sawn through at CD; the weight W hung on there will be just sufficient to break it at E and G. Now restore the connection of the section CD, it will require another weight W to break it there at the same time.

Therefore, when a rafter, or any piece of timber, is firmly connected with the three fixed points G, E, I, it will bear a greater load between any two of them than if its connection with the remote point were removed; and if it be fastened in four points, G, E, I, K, it will be twice as strong in the middle part as without the two remote connections.

One is apt to expect from this that the joist of a floor will be much strengthened by being firmly built in the wall. It is a little strengthened; but the hold which can thus be given it is much too short to be of any sensible service; and it tends greatly to shatter the wall, because, when it is bent down by a load, it forces up the wall with the momentum of a long lever. Judicious builders therefore take care not to bind the joists tight in the wall. But when the joists of adjoining rooms lie in the same direction, it is a great advantage to make them of one piece. They are then twice as strong as when made in two lengths.

18. It is easy to deduce from these premises the strain on any point which arises from the weight of the

beam itself, or from any load which is uniformly diffused over the whole or any part. We may always consider the whole of the weight which is thus uniformly diffused over any part as united in the middle point of that part; and if the load is not uniformly diffused, we may still suppose it united at its centre of gravity. Thus, to know the strain at L arising from the weight of the whole beam, we may suppose the whole weight accumulated in its middle point D. Also the strain at L, arising from the weight of the part ED, is the same as if this weight were accumulated in the middle point *d* of ED; and it is the same as if half the weight of ED were hung on at D. For the real strain at L is the upward pressure at G, acting by the lever GL. Now calling e the weight of the part DE: this upward pressure will be $\frac{e \times dE}{EG}$, or $\frac{\frac{1}{2} e \times DE}{EG}$.

Therefore the strain on the middle of a beam, arising from its own weight, or from any uniform load, is the weight of the beam or its load $\frac{ED}{EG} \times DG$; that is, half the weight of the beam or load multiplied or acting by the lever DG; for $\frac{ED}{EG}$ is $\frac{1}{2}$.

Also the strain at L, arising from the weight of the beam, or the uniform load, is $\frac{1}{2}$ the weight of the beam or load acting by the lever LG. It is therefore proportional to LG, and is greatest of all at D. Therefore a beam of uniform strength throughout, uniformly loaded, will break in the middle.

19. It is of importance to know the relation between the strains arising from the weights of the beams, or from any uniformly diffused load, and the relative strength. We have already seen, that the relative strength is $f\frac{db.d}{m\,l}$, where m is a number to be discovered by experiment for every different species of materials. Leaving out every circumstance but what depends on the dimensions of the beam, viz. d, b, and l, we see that the relative strength is in the proportion of $\frac{d^2 b}{l}$, that is, as the breadth and the square of the depth directly, and the length inversely.

Now, to consider first the strain arising from the weight of the beam itself, it is evident that this weight increases in the same proportion with the depth, the breadth, and the length of the beam. Therefore its power of resisting this strain must be as its depth directly, and the square of its length inversely. To consider this in a more popular manner, it is plain that the increase of breadth makes no change in the power of resisting the actual strain, because the load and the absolute strength increase in the same proportion with the breadth. But by increasing the depth, we increase the resisting section in the same proportion, and therefore the number of resisting fibres and the absolute strength:

but we also increase the weight in the same proportion. This makes a compensation, and the relative strength is yet the same. But by increasing the depth, we have not only increased the absolute strength, but also its mechanical energy: For the resistance to fracture is the same as if the full strength of each fibre was exerted at the point which we called the centre of effort; and we showed, that the distance of this from the under side of the beam was a certain portion (a half, a third, a fourth, &c.) of the whole depth of the beam. This distance is the arm of the lever by which the cohesion of the wood may be supposed to act. Therefore this arm of the lever, and consequently the energy of the resistance, increases in the proportion of the depth of the beam, and this remains uncompensated by any increase of the strain. On the whole, therefore, the power of the beam to sustain its own weight increases in the proportion of its depth. But, on the other hand, the power of withstanding a given strain applied at its extremity, or to any aliquot part of its length, is diminished as the length increases, or is inversely as the length; and the strain arising from the weight of the beam also increases as the length. Therefore the power of resisting the strain actually exerted on it by the weight of the beam, is inversely as the square of the length. On the whole, therefore, the power of a beam to carry its own weight, varies in the proportion of its depth directly, and the square of its length inversely. See also Fairbairn, Hodgkinson, and Tredgold's Works on the Strength of the several materials.

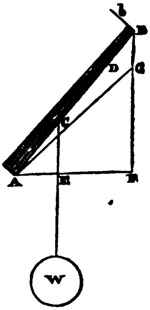
As this strain is frequently a considerable part of the whole, it is proper to consider it apart, and then to reckon only on what remains for the support of any extraneous load.

20. In the next place, the power of a beam to carry any load which is uniformly diffused over its length, must be inversely as the square of the length: for the power of withstanding *any* strain applied to an aliquot part of the length (which is the case here, because the load may be conceived as accumulated at its centre of gravity, the middle point of the beam) is inversely as the length; and the *actual* strain is as the length, and therefore its momentum is as the square of the length. Therefore the power of a beam to carry a weight uniformly diffused over it, is inversely as the square of the length. *N.B.* It is here understood, that the uniform load is of some determined quantity for every foot of the length, so that a beam of double length carries a double load.

21. We have hitherto supposed that the forces which tend to break a beam transversely, are acting in a direction perpendicular to the beam. This is always the case in level floors loaded in any manner; but in roofs, the action of the load tending to break the rafters is oblique, because gravity always acts in vertical lines. It may also frequently happen, that a beam is strained

by a force acting obliquely. This modification of the strain is easily discussed. Suppose that the external force, which is measured by the weight W in Fig. 1, acts in the direction A *w′* instead of AW. Draw C *á* perpendicular to A *w*. Then the momentum of this external force is not to be measured by W × AC, but by W × *á* C. The strain therefore by which the fibres in the section of fracture DC are torn asunder, is diminished in the proportion of CA to C *á*, that is, in the proportion of radius to the sine of the angle CA *á*, which the beam makes with the direction of the external force.

FIG. 3.



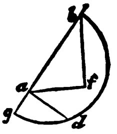
To apply this to our purpose in the most familiar manner, let AB (Fig. 3.) be an oblique rafter of a building, loaded with a weight W suspended to any point C, and thereby occasioning a strain in some part D. We have already seen, that the immediate cause of the strain on D is the reaction of the support which is given to the point B. The rafter may at present be considered as a lever, supported at A, and pulled down by the line CW. This occasions a pressure on B, and the support acts in the opposite direction to the action of the lever, that is, in the direction B *b*, perpendicular to BA. This tends to break the beam in every part. The pressure exerted at B is $\frac{W \times AE}{AB}$, AE being a horizontal line. Therefore the strain at D will be $\frac{W \times AE}{AB} \times BD$. Had the beam been lying horizontally, the strain at D, from the weight W suspended at C, would have been $\frac{W.AC}{AB} \times BD$. It is therefore diminished in the proportion of AC to AE, that is, in the proportion of radius to the cosine of the elevation, or in the proportion of the secant of elevation to the radius.

It is evident, that this law of diminution of the strain is the same whether the strain arises from a load on any part of the rafter, or from the weight of the rafter itself, or from any load uniformly diffused over its length, provided only that these loads act in vertical lines.

22. We can now compare the strength of roofs which have different elevations. Supposing the width of the building to be given, and that the weight of a square yard of covering is also given. Then, because the load on the rafter will increase in the same propor-

tion with its length, the load on the slant side BA of the roof will be to the load of a similar covering on the half AF of the flat roof, of the same width, as AB to AF. But the transverse action of any load on AB, by which it tends to break it, is to that of the same load on AF as AF to AB. The transverse strain therefore, is the same on both, the increase of real load on AB being compensated by the obliquity of its action. But the strengths of beams to resist equal strains, applied to similar points, or uniformly diffused over them, are inversely as their lengths, because the momentum or energy of the strain is proportional to the length. Therefore the power of AB to withstand the strain to which it is really exposed, is to the power of AF to resist its strain as AF to AB. If, therefore, a rafter AG of a certain scantling is just able to carry the roofing laid on it, a rafter AB of the same scantling, but more elevated, will be too weak in the proportion of AG to AB. Therefore steeper roofs require stouter rafters, in order that they may be equally able to carry a roofing of equal weight per square yard. To be equally strong, they must be made broader, or placed nearer to each other, in the proportion of their greater length, or they must be made deeper in the subduplicate proportion of their length. The following easy construction will enable the artist not familiar with computation to proportion the depth of the rafter to the slope of the roof.

FIG. 4.



Let the horizontal line *a f*, Fig. 4, be the proper depth of a beam whose length is half the width of the building; that is, such as would make it fit for carrying the intended tiling laid on a flat roof. Draw the vertical line *f b*, and the line *a b* having the elevation of the rafter; make *a g* equal to *a f*, and describe the semicircle *b d g;* draw *a d* perpendicular to *a b*, *a d* is the required depth. The demonstration is evident.

We have now treated in sufficient detail what relates to the chief strain on the component parts of a roof, namely, what tends to break them transversely; and we have enlarged more on the subject than what the present occasion indispensably required, because the propositions which we have demonstrated are equally applicable to all framings of carpentry, and are even of greater moment in many cases, particularly in the construction of machines. These consist of levers in various forms, which are strained transversely; and similar strains frequently occur in many of the supporting and connecting parts.

23. We proceed, in the next place, to consider the other strains to which the parts of roofs are exposed.

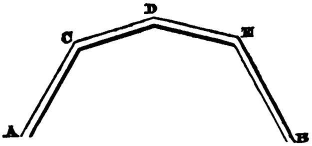
these motions the centre of gravity G will go out of its place, and the vertical line GN will no longer pass through the point where the directions of the supports intersect each other. If the centre of gravity rises by this motion, the body will have a tendency to recover its former position, and it will require force to keep it away from it. In this case the equilibrium may be said to be *stable*, or the body to have *stability*. But if the centre of gravity descends when the body is moved from the position of equilibrium, it will tend to move still farther; and so far will it be from recovering its former position, that it will now fall. This equilibrium may be called a *tottering equilibrium*. These accidents depend on the situations of the points A, B, C, D, E, F; and they may be determined by considering the subject geometrically. It does not much interest us at present; it is rarely that the equilibrium of suspension is tottering, or that of props is stable. It is evident, that if the beam were suspended by lines from the point P, it would have stability, for it would swing like a pendulum round P, and therefore would always tend towards the position of equilibrium. The intersection of the lines of support would still be at P, and the verticle line drawn through the centre of gravity, when in any other situation, would be on that side of P towards which this centre has been moved. Therefore, by the rules of pendulous bodies, it tends to come back. This would be more remarkably the case if the points of suspension C and D be on the same side of the point P with the points of attachment A and B; for in this case the new point of intersection of the lines of support would shift to the opposite side, and be still farther from the vertical line through the new position of the centre of gravity. But if the point of suspension and of attachment are on opposite sides of P, the new point of intersection may shift to the same side with the centre of gravity, and lie beyond the vertical line; in this case the equilibrium is tottering. It is easy to perceive, too, that if the equilibrium of suspension from the points C and D be stable, the equilibrium on the props AE and BF must be tottering. It is not necessary for our present purpose to engage more particularly in this discussion.

It is plain that, with respect to the mere momentary equilibrium, there is no difference in the support by threads, or props, or planes, and we may substitute the one for the other. We shall find this substitution extremely useful, because we easily conceive distinct notions of the support of a body by strings.

Observe farther, that if the whole figure be inverted, and strings be substituted for props, and props for strings, the equilibrium will still obtain: for by comparing Fig. 5 with Fig. 6, we see that the vertical line through the centre of gravity will pass through the intersection of the two strings or props; and this is all that is necessary for the equilibrium: only it must be observed in the substitution of props for threads, and of threads for props, that if it be done without inverting the whole figure, a stable equilibrium becomes a tottering one, and *vice versâ.*

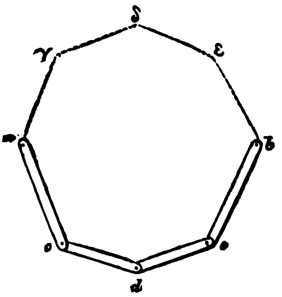
This is a most useful proposition, especially to the unlettered artisan, and enables him to make a practical use of problems which the greatest mechanical geniuses have found no easy task to solve. An instance will show the extent and utility of it. Suppose it were required to make a mansard or kirb roof whose width is AB

Fig. 7.



(Fig. 7), and consisting of the four equal rafters AC, CD, DE, EB. There can be no doubt but that its best form is that which will put all the parts in equilibrio, so that no ties or stays may be necessary for opposing the unbalanced thrust of any part of it. Make a chain $a\ c\ d\ e\ b$ (Fig. 8) of four equal pieces, loosely connected by pin-joints, round which the parts are perfectly moveable. Suspend this from two pins a, b, fixed in a horizontal line. This chain or festoon will arrange itself in such a form that its parts are in equilibrio. Then we know that if the figure be inverted, it will compose the frame or truss of a kirb-roof $a\ \gamma\ \delta\ \epsilon\ b$, which is also in equilibrio, the thrusts of the

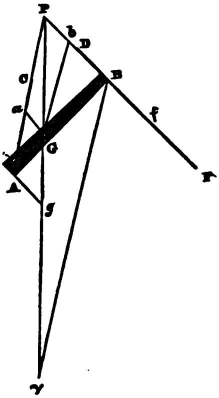
Fig. 8.



pieces balancing each other in the same manner that the mutual pulls of the hanging festoon *a c d e b* did. If the proportion of the height *d f* to the width *a b* is not such as pleases, let the pins *a*, *b*, be placed nearer or mere distant, till a proportion between the width and height is obtained which pleases, and then make the figure ACDEB Fig. 7 similar to it. It is evident that this proposition will apply in the same manner to the determination of the form of an arch of a bridge; but this is not a proper place for a farther discussion.

We are now able to compute all the thrusts and other pressures which are exerted by the parts of a roof on each other and on the walls. Let AB (Fig. 9) be a beam standing any how obliquely, and G its centre of gravity. Let us suppose that the ends of it are supported in any directions AC, BD, by strings, props, or planes. Let these directions meet in the point P of

FIG. 9.



the vertical line PG passing through its centre of gravity. Through G draw lines G *a*, G *b* parallel to PB, PA. Then

$$\left.\begin{array}{l}\text{The weight of the beam}\\ \text{The pressure or thrust at A}\\ \text{The pressure at B}\end{array}\right\}\text{ are proportional to }\left\{\begin{array}{l}\text{PG}\\ \text{P}\,a\\ \text{P}\,b.\end{array}\right.$$

For when a body is in equilibrio between three forces, these forces are proportional to the sides of a triangle which have their directions.

In like manner, if A *g* be drawn parallel to P *b*, we shall have

$$\left.\begin{array}{l}\text{Weight of the beam}\\ \text{Thrust on A}\\ \text{Thrust on B}\end{array}\right\}\text{ proportional to }\left\{\begin{array}{l}\text{P}\,g\\ \text{P A}\\ \text{B}\,g\end{array}\right.$$

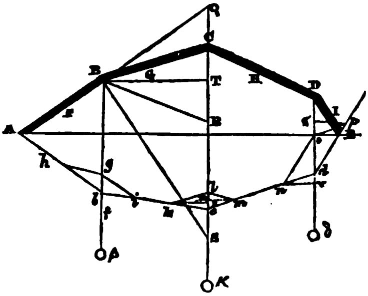
Or, drawing B γ parallel to P a

$$\left.\begin{array}{l}\text{Weight of beam}\\ \text{Thrust at A}\\ \text{Thrust at B}\end{array}\right\}\text{ are proportional to }\left\{\begin{array}{l}P\gamma\\ B\gamma\\ PB.\end{array}\right.$$

It cannot be disputed that, if strength alone be considered, the proper form of a roof is that which puts the whole in equilibrio, so that it would remain in that shape although all the joints were perfectly loose or flexible. If it has any other shape, additional ties or braces are necessary for preserving it, and the parts are unnecessarily strained. When this equilibrium is obtained, the rafters which compose the roof are all acting on each other in the direction of their lengths: and by this action, combined with their weights, they sustain no strain but that of compression, the strain of all others that they are the most able to resist. We may consider them as so many inflexible lines having their weights accumulated in their centres of gravity. But it will allow an easier investigation of the subject, if we suppose the weights to be at the joints, equal to the real vertical pressures which are exerted on these points. These are very easily computed; for it is plain, that the weight of the beam AB (Fig. 9.) is to the part of this weight that is supported at B as AB to AG. Therefore, if W represent the weight of the beam, the vertical pressure at B will be $W \times \frac{AG}{AB}$, and the vertical pressure at A will be $W \times \frac{BG}{AB}$. In like manner, the prop BF being considered as another beam, and f as its centre of gravity, and w as its weight, a part of this weight, equal to $w \times \frac{f\text{F}}{\text{BF}}$, is supported at B, and the whole vertical pressure at B is $\text{W} \times \frac{\text{AG}}{\text{AB}} + w \times \frac{f\text{F}}{\text{BF}}$. And thus we greatly simplify the construction of the mutual thrusts of roof frames. We need hardly observe, that although these pressures by which the parts of a frame support each other in opposition to the vertical action of gravity, are always exerted in the direction of the pieces, they may be resolved into pressures acting in any other direction which may engage our attention.

All that we propose to deliver on this subject at present may be included in the following proposition.

Fig. 10.



Let ABCDE (Fig. 10.) be an assemblage of rafters in a vertical plane, resting on two fixed points A and E in a horizontal line, and perfectly moveable round all the joints A, B, C, D, E; and let it be supposed to be in equilibrio, and let us investigate what adjustment of the different circumstances of weight and inclination of its different parts is necessary for producing this equilibrium.

Let F, G, H, I, be the centres of gravity of the different rafters, and let these letters express the weights of each. Then (by what has been said above (the weight which presses B directly downwards is $F \times \frac{AF}{AB} + G \times \frac{CG}{BC}$. The weight on C is in like manner $G \times \frac{BG}{BC} + H \times \frac{DH}{CD}$ and that on D is $H \times \frac{CH}{CD} + I \times \frac{EI}{DE}$.

Let A *b c d* E be the figure ABCDE inverted, in the manner already described. It may be conceived as a thread fastened at A and E, and loaded at *b*, *c*, and *d*, with the weights which are really pressing on B, C, and D. It will arrange itself into such a form that all will be in equilibrio. We may discover this form by means of this single consideration, that any part *b c* of the thread is equally stretched throughout in the direction of its length. Let us therefore investigate the proportion between the weight β which we suppose to be pulling the point *b* in the vertical direction $b\,\beta$ to the weight δ, which is pulling down the point *d* in a similar manner. It is evident, that since AE is a horizontal line, and the figures A *b c d* E and ABCDE equal and similar, the lines B *b*, C *c*, D *d*, are vertical. Take *b f* to represent the weight hanging at *b*. By stretching the threads *b* A and *b c* it is set in opposition to the contractile powers of the threads, acting in the directions *b* A and *b c*, and it is in immediate equilibrio with the equivalent of these two contractile forces. Therefore make *b g* equal to *b f*, and make it the diagonal of a parallelogram *h b i g*. It is evident that *b h*, *b i*, are the forces exerted by the threads *b* A, *b c*. Then, seeing that the thread *b c* is equally stretched in both directions, make *c k* equal to *b i*; *c k* is the contractile force which is excited at *c* by the weight which is hanging there. Draw *k l* parallel to *c d*, and *l m* parallel to *b c*. The force *l c* is the equivalent of the contractile forces *c k*, *c m*, and is therefore equal and opposite to the force of gravity acting at C. In like manner, make $d\,n = c\,m$, and complete the parallelogram *n d p o*, having the vertical line *o d* for its diagonal. Then *d n* and *d p* are the contractile forces excited at *d*, and the weight hanging there must be equal to *o d*.

Therefore, the load at *b* is to the load at *d* as *b g* to *d o*. But we have seen that the compressing forces at B, C, D, may be substituted for the extending forces at *b*, *c*, *d*. Therefore the weights at B, C, D, which produce the compressions, are equal to the weights at *b*, *c*, *d*, which produce the extensions. Therefore

$$b\,g : d\,o = \mathrm{F} \times \frac{\mathrm{AF}}{\mathrm{AB}} + \mathrm{G} \times \frac{\mathrm{CG}}{\mathrm{BC}} : \mathrm{H} \times \frac{\mathrm{CH}}{\mathrm{CD}} + \mathrm{I} \times \frac{\mathrm{EI}}{\mathrm{DE}}.$$

Let us inquire what relation there is between this proportion of the loads upon the joints at B and D, and the angles which the rafters make at these joints with each other, and with the horizon or the plumb lines. Produce AB till it cut the vertical C c in Q; draw BR parallel to CD, and BS parallel to DE. The similarity of the figures ABCDE and A b c d E, and the similarity of their position with respect to the horizontal and plumb lines, show, without any further demonstration, that the triangles QCB and $g\,b\,i$ are similar, and that QB: BC $= g\,i : i\,b, = h\,b : i\,b$. Therefore QB is to BC as the contractile force exerted by the thread A b to that exerted by $b\,c$; and therefore QB is to BC as the compression of BA to the compression on BC. Then, because $b\,i$ is equal to $c\,k$, and the triangles CBR and $c\,k\,l$ are similar, CB : BR $= c\,k : k\,l, = c\,k : c\,m$, and CB is to BR as the compression on CB to the compression on CD. And, in like manner, because $c\,m = d\,n$, we have BR to BS as the compression on DC to the compression on DE. Also BR : RS $= n\,d : d\,o$, that is, as the compression on DC to the load on D. Finally, combining all these ratios

$$\mathrm{QC} : \mathrm{CB} = g\,b : b\,i, = g\,b : k\,c$$
$$\mathrm{CB} : \mathrm{BR} = k\,c : k\,l, = k\,c : d\,n$$
$$\mathrm{BR} : \mathrm{BS} = n\,d : n\,o = d\,n : n\,o$$
$$\mathrm{BS} : \mathrm{RS} = n\,o : d\,o = n\,o : d\,o, \text{ we have finally}$$
$$\mathrm{QC} : \mathrm{RS} = g\,b : o\,d = \text{Load at B} : \text{Load at D}.$$

Now

$$\mathrm{QC} : \mathrm{BC} = f,\ \mathrm{QBC} : f,\ \mathrm{BQC}, = f,\ \mathrm{ABC} : f,\ \mathrm{AB}\,b$$
$$\mathrm{BC} : \mathrm{BR} = f,\ \mathrm{BRC} : f,\ \mathrm{BCR}, = f,\ \mathrm{CD}d : f,\ b\,\mathrm{BC}$$

$$\mathrm{BR} : \mathrm{RS} = f,\ \mathrm{BSR} : f,\ \mathrm{RBS}, = f,\ d\,\mathrm{DE} : f,\ \mathrm{CDE}$$

Therefore

$\mathrm{QC} : \mathrm{RS} = f,\ \mathrm{ABC}.\ f,\ \mathrm{CD}\,d.\ f,\ d\,\mathrm{DE} : f,\ \mathrm{CDE}.\ f,\ \mathrm{AB}\,b.\,f,\ b\,\mathrm{BC}.$

Or

$$\mathrm{QC} : \mathrm{RS} = \frac{f,\mathrm{ABC}}{f,\mathrm{AB}\,b,\,f\,\mathrm{CB}b} : \frac{f,\mathrm{CDE}}{f,d\,\mathrm{DC}.\,f,d\,\mathrm{DE}}.$$

That is, the loads on the different joints are as the sines of the angles at these joints directly, and as the products of the sines of the angles which the rafters make with the plumb-lines inversely.

Or, the loads are as the sines of the angles of the joints directly, and as the products of the cosines of the elevations of the rafters inversely.

Or, the loads at the joints are as the sines of the angles at the joints, and as the products of the secants of elevation of the rafters, jointly: for the secants of angles are inversely as the cosines.

Draw the horizontal line BT. It is evident, that if this be considered as the radius of a circle, the lines BQ, BC, BR, BS, are the secants of the angles which these lines make with the horizon. And they are also as the thrusts of those rafters to which they are parallel. Therefore, the thrust which any rafter makes in its own direction is as the secant of its elevation.

The horizontal thrust is the same at all the angles. For $i\,\iota, = k\,\kappa, = m\,\mu, = n\,\nu, = p\,\pi$. Therefore both walls are equally pressed out by the weight of the roof.

We can find its quantity by comparing it with the load on one of the joints:

Thus, $QC : CB = f, ABC : f, ABb$

$BC : BT = \text{Rad.} : f, BCT, = \text{Rad.} : f, CB\,b$

Therefore, $QC : BT = \text{Rad.} \times f, ABC : f, b\,BA \times f, b\,BC$.

24. It deserves remark, that the lengths of the beams do not affect either the proportion of the load at the different joints, nor the position of the rafters. This depends merely on the weights at the angles. If a change of length affects the weight, this indeed affects the form also: and this is generally the case. For it seldom happens, indeed it never should happen, that the weight on rafters of longer bearing are not greater. The covering alone increases nearly in the proportion of the length of the rafter.

If the proportion of the weights at B, C, and D, are given, as also the position of any two of the lines, the position of all the rest is determined.

If the horizontal distances between the angles are all equal, the forces on the different angles are proportional to the verticals drawn on the lines through these angles from the adjoining angle, and the thrusts from the adjoining angles are as the lines which connect them.

If the rafters themselves are of equal lengths, the weights at the different angles are as these verticals and as the secants of the elevation of the rafters jointly.

25. This proposition is very fruitful in its prac-

tical consequences. It is easy to perceive that it contains the whole theory of the construction of arches; for each stone of an arch may be considered as one of the rafters of this piece of carpentry, since all is kept up by its mere equilibrium.* We may have an opportunity of afterwards exhibiting some very elegant and simple solutions of the most difficult cases of this important problem; and we now proceed to make use of the knowledge we have acquired for the construction of roofs.

26. We mentioned by-the-by, a problem which is not unfrequent in practice, to determine the best form of a kirb-roof. Mr. Couplet, of the Royal Academy of Paris, has given a solution of it in an elaborate memoir in 1726, occupying several lemmas and theorems.

Let AE (Fig. 11.) be the width, and CF the height; it is required to construct a roof ABCDE whose rafters AB, BC, CD, DE, are all equal, and which shall be in equilibrio.

Draw CE, and bisect it perpendicularly in H by the line DHG, cutting the horizontal line AE in G. About the centre G, with the distance GE, describe the circle EKC. It must pass through C, because CH is equal to HE and the angles at H are equal. Draw HK parallel to FE, cutting the circumference in K. Draw CK, cutting GH in D. Join CD, ED; these lines are the rafters of half of the roof required.

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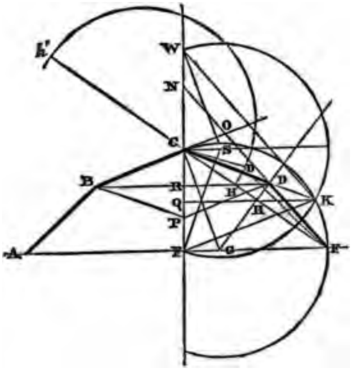
* Gwilt on the *Equilibrium Arches.* 8vo. Lond. 1839, p. 14.

FIG. 11.



We prove this by showing, that the loads in the angles C and D are equal. For this is the proportion which results from the equality of the rafters, and the extent of surface of the uniform roofing which they are supposed to support. Therefore produce ED till it meet the vertical FC in N; and having made the side CBA similar to CDE, complete the parallelogram BCDP, and draw DB, which will bisect CP in R, as the horizontal line KH, bisects CF in Q. Draw KF, which is evidently parallel to DP. Make CS perpendicular to CF, and equal to FG; and about S, with the radius SF, describe the circle FKW. It must pass through K, because SF is equal to CG, and CQ = QF. Draw WK, WS, and produce BC, cutting ND in O.

The angle WKF at the circumference is one half of the angle WSF at the centre, and is therefore equal to WSC, or CGF. It is therefore double of the angle CEF or ECS. But ECS is equal to ECD and DCS, and ECD is one half of NDC, and DCS is one half of DCO, or CDP. Therefore the angle WKF is equal to NDP, and WK is parallel to ND, and CF is to CW as CP to CN; and CN is equal to CP. But it has been shown above, that CN and CP are as the loads upon D and C. These are therefore equal, and the frame ABCDE is in equilibrio.

A comparison of this solution with that of Mr. Couplet will show its great advantage in respect of simplicity and perspicuity. And the intelligent reader can easily adapt the construction to any proportion between the rafters AB and BC, which other circumstances, such as garret-room, &c., may render convenient. The construction must be such that NC may be to CP as CD to $\frac{CD+DE.}{2}$. Whatever proportion of AB to BC is assumed, the point D′ will be found in the circumference of a semicircle H′ D′ h', whose centre is in the line CE, and having AB : BC = CH′ : HE′, = $c\ h' : h'$ E. The rest of the construction is simple.

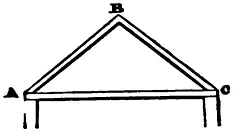
In buildings which are roofed with slate, tile, or shingles, the circumstance which is most likely to limit the construction is the slope of the upper rafters CB, CD. This must be sufficient to prevent the penetration of rain, and the stripping by the winds. The only circumstance left in our choice in this case is the proportion of the rafters AB and BC. Nothing is easier than making NC to CP in any desired proportion when the angle BCD is given.

27. We need not repeat that it is always a desirable thing to form a truss for a roof in such a manner that it shall be in equilibrio. When this is done, the whole force of the struts and braces which are added to it is employed in preserving this form, and no part is expended in unnecessary strains. For we must now observe, that the equilibrium of which we have been treating is always of that kind which we call the tottering, and the roof requires stays, braces, or hanging timbers, to give it stiffness, or keep it in shape. We have also said enough to enable any reader, acquainted with the most elementary geometry and mechanics, to compute the transverse strains and the thrusts to which the component parts of all roofs are exposed.

28. It only remains now to show the general maxims by which all roofs must be constructed, and the circumstances which determine their excellence. In doing this we shall be exceedingly brief, and almost content ourselves with exhibiting the principal forms, of which the endless variety of roofs are only slight modifications. We shall not trouble the reader with any account of such roofs as receive part of their support from the interior walls, but confine ourselves to the more difficult problem of throwing a roof over a wide building, without any intermediate support; because when such roofs are constructed in the best manner, that is, deriving the

greatest possible strength from the materials employed, the best construction of the others is necessarily included. For all such roofs as rest on the middle walls are roofs of smaller bearing. The only exception deserving notice is the roofs of churches, which have aisles separated from the nave by columns. The roof must rise on these. But if it is of an arched form internally, the horizontal thrusts must be nicely balanced, that they may not push the columns aside.*

Fig. 12.



29. The simplest notion of a roof-frame is, that it consists of two rafters AB and BC (Fig. 12.), meeting in the ridge B.

Even this simple form is susceptible of better and worse. We have already seen, that when the weight of a square yard of covering is given, a steeper roof requires stronger rafters, and that when the scantling of the timbers is also given, the relative strength of a rafter is inversely as its length. But there is now another circumstance to be taken into the account, viz.,

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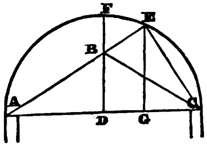
* For modern examples of largely spanned constructed Iron Roofs, see *Atlas* to these vols., 124* in the series.

the support which one rafter leg gives to the other. The best form of a rafter will therefore be that in which the relative strength of the legs, and their mutual support, give the greatest product. Describe on the width

FIG. 13.



AC, Fig. 13, the semicircle ACF, and bisect it by the radius FD. Produce the rafter AB to the circumference in E, join EC, and draw the perpendicular EG. Now AB : AD :: AC : AE, and $AE = \frac{AD \times AC}{AB}$, and AE is inversely as AB, and may therefore represent its strength in relation to the weight actually lying on it. Also the support which CB gives to AB is as CE, because CE is perpendicular to AB. Therefore the form which renders AE × EC a maximum seems to be that which has the greatest strength. But AC : AE = EC : EG, and $EG = \frac{AE \, . \, EC}{AC}$, and is therefore proportional to AE.EC. Now EG is a maximum when B is in F, and a square pitch is in this respect the strongest. But it is very doubtful whether this construction is deduced from just principles. There is another strain to which the leg AB is exposed, which is not taken into the account. This arises from the curvature which it unavoidably acquires by the transverse pressure of its load. In this state it is pressed in its own direction by the abutment and load of the other leg. The relation between this strain and the resistance of the piece is not very distinctly known. Euler has given a dissertation on this subject (which is of great importance, because it affects posts and pillars of all kinds; and it is very well known that a post of ten feet long and six inches square will bear with great safety a weight, which would crush a post of the same scantling and 20 feet long in a minute); but his determination has not been acquiesced in by the first mathematicians. Now it is in relation to these two strains that the strength of the rafter should be adjusted. The firmness of the support given by the other leg is of no consequence, if its own strength is inferior to the strain. The force which tends to crush the leg AB, by compressing it in its curved state, is to its weight as AB to BD, as is easily seen by the composition of forces; and its incurvation by this force has a relation to it, which is of intricate determination. It is contained in the properties demonstrated by Bernoulli of the elastic curve. This determination also includes the relation between the curvature and the length of the piece. But the whole of this seemingly simple problem is of much more difficult investigation than is generally supposed.

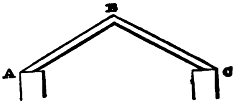
Reasons of economy have made carpenters prefer a low pitch; and although this does diminish the support given by the opposite leg faster than it increases the relative strength of the other, this is not of material consequence, because the strength remaining in the opposite leg is still very great; for the supporting leg is acting against compression, in which case it is vastly stronger than the supported leg acting against a transverse strain.

30. But a roof of this simplicity will not do in most cases. There is no notice taken in its construction of the thrust which it exerts on the walls. Now this is the strain which is the most hazardous of all. Our ordinary walls, instead of being able to resist any considerable strain pressing them outwards, require, in general, some ties to keep them on foot. When a person thinks of the thinness and height of the walls of even a strong house, he will be surprised that they are not blown down by any strong blast of wind. A wall of three feet thick, and 60 feet high, could not withstand a wind blowing at the rate of 30 feet *per* second (in which case it acts with a force considerably exceeding two pounds on every square foot), if it were not stiffened by cross walls, joists, and roof, which all help to tie the different parts of the building together.

31. A carpenter is therefore exceedingly careful to avoid every horizontal thrust, or to oppose them by other forces. And this introduces another essential

part into the construction of a roof, namely the *tie* or *beam** AC, (Fig. 14.), laid from wall to wall, binding

FIG. 14.



the feet A and C of the rafters together. This is the sole office of the beam; and it should be considered in no other light than as a string to prevent the roof from pushing out the walls. It is indeed used for carrying the ceiling of the apartments under it: and it is even made to support a flooring. But, considered as making part of a roof, it is merely a string; and the strain which it withstands tends to tear its parts asunder. It therefore acts with its whole absolute force, and a very small scantling would suffice if we could contrive to fasten it firmly enough to the foot of the rafter. If it is of oak, we may safely subject it to a strain of three tons for every square inch of its section. And fir will safely bear a strain of two tons for every square inch. But we are obliged to give the tie-beam much larger dimensions, that we may be able to connect it with the foot of the rafter by a mortise and tenon. Iron straps are also frequently added. By

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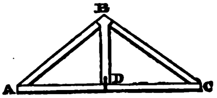
* Tredgold's *Carpentry*, 4to., first edition, 1820.

attending to this office of the tie-beam, the judicious carpenter is directed to the proper form of the mortise and tenon and of the strap.* We shall consider both of these in a proper place, after we become acquainted with the various strains at the joints of a roof.

These large dimensions of the tie-beam allow us to load it with the ceilings without any risk, and even to lay floors on it with moderation and caution. But when it has a great bearing or span, it is very apt to bend downwards in the middle, or, as the workmen term it, to sway or swag; and it requires a support. The question is, where to find this support? What fixed points can we find with which to connect the middle of the tie-beam? Some ingenious carpenter thought of suspending it from the ridge by a piece of timber BD (Fig. 15.) called by our carpenters the *king-post*. It must be acknowledged that there was great ingenuity in this thought. It was also perfectly just. For the weight of the rafters BA, BC, tends to make them fly out at the foot. This is prevented by the

FIG. 15.



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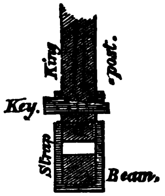
* Tredgold's *Carpentry;* also, in p. 97, note of Col. Waddington's Construction at Bombay, edit. 1853.

tie-beam, and this excites a pressure, by which they tend to compress each other. Suppose them without weight, and that a great weight is laid on the ridge B. This can be supported only by the butting of the rafters in their own directions AB and CB, and the weight tends to compress them in the opposite directions, and, through their intervention, to stretch the tie-beam. If neither the rafters can be compressed, nor the tie-beam stretched, it is plain that the triangle A B C must retain its shape, and that B becomes a fixed point, very proper to be used as a point of suspension. To this point, therefore, is the tie-beam suspended by means of the king-post. A common spectator, unacquainted with carpentry, views it very differently, and the tie-beam appears to him to carry the roof. The king-post appears a pillar resting on the beam, whereas it is really a string; and an iron rod of one-sixteenth of the size would have done just as well. The king-post is sometimes mortised into the tie-beam, and pins put through the joint, which gives it more the look of a pillar with the roof resting on it. This does well enough in many cases. But the best method is to connect them by an iron strap, like a stirrup, which is bolted at its upper ends into the king-post, and passes round the tie-beam. In this way a space is commonly left between the end of the king-post and the upper side of the tie-beam. Here the beam plainly appears hanging in the stirrup; and this method allows us to restore the beam to an exact level, when it has sunk by the unavoidable compression or other yielding of the parts. The holes in the sides of the iron strap are made oblong instead of round; and the bolt which is drawn through all is made to taper on the under side; so that driving it farther draws the tie-beam upwards. A notion of this may be formed by looking at Fig. 16, which is a section of the post and beam.

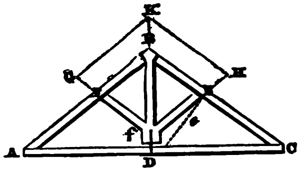
FIG. 16.



It requires considerable attention, however, to make this suspension of the tie-beam sufficiently firm. The top of the king-post is cut into the form of the arch-stone of a bridge, and the heads of the rafters are firmly mortised into this projecting part. These projections are called joggles, and are formed by working the king-post out of a much larger piece of timber, and cutting off the unnecessary wood from the two sides; and, lest all this should not be sufficient, it is usual in great works to add an iron plate or strap of three branches, which are bolted into the heads of the king-post and rafters.

The rafters, though not so long as the beam, seem to stand as much in need of something to prevent their bending, for they carry the weight of the covering. This cannot be done by suspension, for we have no fixed points above them: But we have now got a very firm point of support at the foot of the king-post.

FIG. 17.

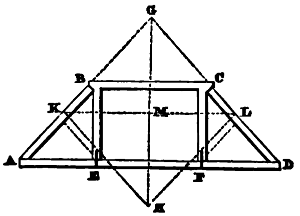


Braces or *struts*, ED, FD, Fig. 17, are put under the middle of the rafters, where they are slightly mortised, and their lower ends are firmly mortised into joggles formed on the foot of the king-post. As these braces are very powerful in their resistance to compression, and the king-post equally so to resist extension, the points E and F may be considered as fixed; and the rafters being thus reduced to half their former length, have now four times their former relative strength.

32. Roofs do not always consist of two sloping sides meeting in a ridge. They have sometimes a flat on the top, with two sloping sides. They are sometimes formed with a double slope, and are called *kirb* or *mansard roofs.* They sometimes have a valley in

the middle, and are then called M roofs. Such roofs require another piece which may be called the *truss-beam*, because all such frames are called *trusses*, probably from the French word *trousse*, because such roofs are like portions of plain roofs, *troussés* or shortened.

FIG. 18.



A flat-topped roof is thus constructed. Suppose that there are three rafters AB, BC, CD (Fig. 18.) of which AB and CD are equal, and BC horizontal. It is plain that they will be in equilibrio, and the roof have no tendency to go to either side. The tie-beam AD withstands the horizontal thrusts of the whole frame, and the two rafters AB and CD are each pressed in their own directions in consequence of their butting with the middle rafter or truss-beam BC. It lies between them like the key stone of an arch. They lean towards it, and it rests on them. The pressure which the truss-beam and its load excites on the two rafters is the very same as if the rafters were produced till they meet in G, and a weight were laid on these equal to that of BC and its load. If therefore the truss-beam is of a scantling sufficient for carrying its own load, and withstanding the compression from the two rafters, the roof will be equally strong (while it keeps its shape) as the plain roof AGD furnished with king-post and braces. We may conceive this another way. Suppose a plain roof AGD, without braces to support the middle B and C of the rafters. Then let a beam BC be put in between the rafters, butting upon little notches cut in the rafters. It is evident that this must prevent the rafters from bending downwards, because the points B and C cannot descend, moving round the centres A and D, without shortening the distance BC between them. This cannot be without compressing the beam BC. It is plain that BC may be wedged in, or wedges driven in between its ends B and C and the notches in which it is lodged. These wedges may be driven in till they even force out the rafters GA and GD. Whenever this happens, all the mutual pressure of the heads of these rafters at G is taken away, and the parts GB and GC may be cut away, and the roof ABCD will be as strong as the roof AGD furnished with the king-post and braces, because the truss-beam gives a support of the same kind at B and C as the brace would have done.

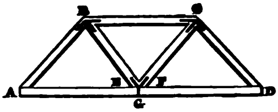
But this roof ABCD would have no firmness of shape. Any addition of weight on one side would destroy the equilibrium at the angle, would depress that angle, and cause the opposite one to rise. To give it stiffness, it must either have ties or braces, or something partaking of the nature of both. The usual method of framing is to make the heads of the rafters butt on the joggles of two side-posts BE and CF, while the truss-beam, or strut, as it is generally termed by the carpenters, is mortised square into the inside of the heads. The lower ends E and F of the side-posts are connected with the tie-beam either by mortises or straps.

This construction gives firmness to the frame; for the angle B cannot descend in consequence of any inequality of pressure, without forcing the other angle C to rise. This it cannot do, being held down by the post CF. And the same construction fortifies the tie-beam, which is now suspended at the points E and F from the points B and C, whose firmness we have just now shown.

33. But although this roof may be made abundantly strong, it is not quite so strong as the plain roof AGD of the same scantling. The compression which BC must sustain in order to give the same support to the rafters at B and C that was given by braces properly placed, is considerably greater than the compression of the braces. And this strain is an addition to the transverse strain which BC gets from its own load. This form also necessarily exposes the tie-beam to cross strains. If BE is mortised into the tie-beam, then the strain which tends to depress the angle ABC presses on the tie-beam at E transversely, while a con-

trary strain acts on F, pulling it upwards. These strains however are small; and this construction is frequently used, being susceptible of sufficient strength, without much increase of the dimensions of the timbers; and it has the great advantage of giving free room in the garrets. Were it not for this, there is a much more perfect form represented in Fig. 19. Here the two posts BE, CF, are united below. All transverse action on the tie-beam is now entirely removed. We are almost disposed to say that this is the strongest roof of the same width and slope: for if the iron-strap which connects the pieces BE, CF, with the tie-beam have a large bolt G through it, confining it to one point of the beam, there are five points A, B, C, D, G, which cannot change their places, and there is no transverse strain in any of the connections.

FIG. 19.



When the dimensions of the building are very great, so that the pieces AB, BC, CD, would be thought too weak for withstanding the cross strains, braces may be added as is expressed in Fig. 18 by the dotted lines. The reader will observe that it is not meant to leave the top flat externally: it must be raised a little in the middle to carry off the rain. But this must not be done by incurvating the beam BC. This would soon be crushed, and spring upwards. The slopes must be given by pieces of timber added above the strutting beam.

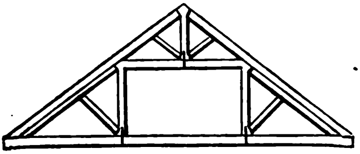
34. And thus we have completed a frame of a roof. It consists of these principal members: The rafters, which are immediately loaded with the covering; the tie-beam, which withstands the horizontal thrust by which the roof tends to fly out below and push out the walls; the king-posts, which hang from fixed points and serve to uphold the tie-beam, and also to afford other fixed points on which we may rest the braces which support the middle of the rafters; and lastly, the truss or strutting-beam, which serves to give mutual abutment to the different parts which are at a distance from each other. The rafters, braces, and trusses, are exposed to compression, and must therefore have not only cohesion but stiffness. For if they bend, the prodigious compressions to which they are subjected would quickly crush them in this bended state. The tie-beams and king-posts, if performing no other office but supporting the roof, do not require stiffness, and their places might be supplied by ropes, or by rods of iron of one-tenth part of the section that even the smallest oak stretcher requires. These members require no greater dimensions than what is necessary for giving sufficient joints, and any more is a needless expense and load. All roofs, however complicated, consist of these essen-

tial parts, and if pieces of timber are to be seen which perform none of these offices, they must be pronounced useless, and they are frequently hurtful, by producing cross strains in some other piece. In a roof properly constructed there should be no such strains. All the timbers, except those which immediately carry the covering, should be either pushed or drawn in the direction of their length. And this is the rule by which a roof should always be examined.

35. These essential parts are susceptible of numberless combinations and varieties. But it is a prudent maxim to make the construction as simple, and consisting of as few parts, as possible. We are less exposed to the imperfections of workmanship, such as loose joints, &c. Another essential harm arises from many pieces, by the compression and the shrinking of the timber in the cross direction of the fibres. The effect of this is equivalent to the shortening of the piece which butts on the joint. This alters the proportions of the sides of the triangle on which the shape of the whole depends. Now in a roof such as Fig. 18, there is twice as much of this as in the plain pent roof, because there are two posts. And when the direction of the butting pieces is very oblique to the action of the load, a small shrinking permits a great change of shape. Thus in a roof of what is called pediment pitch, where the rafters make an angle of 30 degrees with the horizon, half an inch compression of the king-post will pro-

duce a sagging of an inch, and occasion a great strain on the tie-beam if the posts are mortised into it.

FIG. 20.



We would therefore recommend Fig. 20 as a proper construction of a trussed roof, preferable to that which is generally used, and the king-post which is placed in it may be employed to support the upper part of the rafters, and also for preventing the strut-beam from bending in either direction in consequence of its great compression. It will also give a suspension for the great burdens which are sometimes necessary in a theatre. The machinery has no other firm points to which it can be attached; and the portion of the single rafters which carry this king-post are but short, and therefore may be considerably loaded with safety.

86. Thus have we given an elementary, but a rational or scientific, account of this important part of the art of carpentry. It is such, that any practitioner, with the trouble of a little reflection, may always proceed with confidence, and without resting any part of his practice on the vague notions which habit may have

given him of the strength and supports of timbers, and of their manner of acting. That these frequently mislead, is proved by the mutual criticisms which are frequently published by the rivals in the profession. They have frequently sagacity enough (for it can seldom be called science) to point out glaring blunders; and any person who will look at some of the performances of recent architects and builders of acknowledged reputation, will readily see them distinguishable from the works of inferior builders by simplicity alone. A man without principles is apt to consider an intricate construction as ingenious and effectual; and such roofs sometimes fail merely by being ingeniously loaded with timber, but more frequently still by the wrong action of some useless piece, which produces strains that are transverse to other pieces, or which, by rendering some points too firm, cause them to be deserted by the rest in the general subsiding of the whole. Instances of this kind are pointed out by Price and by Tredgold. Nothing shows the skill of a carpenter more than the distinctness with which he can foresee the changes of shape which must take place in a short time in every roof. A knowledge of this will often correct a construction which the mere mathematician thinks unexceptionable, because he does not reckon on the actual compression which must obtain, and imagines that his triangles, which sustain no cross strains, invariably retain their shape till the pieces break. The sagacity of the experienced carpenter is not, however, enough without science for perfecting the art. But when he knows how much a particular piece will yield to compression in one case, science will tell him, and nothing but science can do it, what will be the compression of the same piece in another very different case. Thus he learns how far it will now yield, and then he proportions the parts so to each other, that when all have yielded according to their strains, the whole is of the shape he wished to produce, and every joint is in a state of firmness. It is here that we observe the greatest number of improprieties. The iron straps are frequently in positions not suited to the actual strain on them, and they are in a state of violent twist, which both tends strongly to break the strap, and to cripple the pieces which they surround.

In like manner, we frequently see joints or mortises in a state of violent strain on the tenons, or on the heels and shoulders. The joints were perhaps properly shaped to the primitive form of the truss; but by its settling, the bearing on the push is changed: the brace, for example, in a very low pitched roof, comes to press with the upper part of the shoulder, and, acting as a powerful lever on the tenon, breaks it. In like manner, the lower end of the brace, which at first butted firmly and squarely on the joggle of the king-post, now presses with one corner with prodigious force, and seldom fails to splinter off on that side. We cannot help recommending a maxim of Mr. Perronet, the celebrated engineer of France, as a golden rule, viz. to make all the shoulders of butting pieces in the form of an arch of a circle, having the opposite end of the piece for its centre. Thus, in Fig. 18 if the joggle point B be of this form, having A for its centre, the sagging of the roof will make no partial bearing at the joint: for in the sagging of the roof, the piece AB turns or bends round the centre A, and the counter-pressure of the joggle is still directed to A, as it ought to be. We have just now said *bends* round A. This is too frequently the case, and it is always very difficult to give the tenon and mortise in this place a true and invariable bearing. The rafter pushes in the direction BA, and the beam resists in the direction AD. The abutment should be perpendicular to neither of these but in an intermediate direction, and it ought also to be of a curved shape. But the carpenters perhaps think that this would weaken the beam too much to give it this shape in the shoulder; they do not even aim at it in the heel of the tenon. The shoulder is commonly even with the surface of the beam. When the bearing therefore is on this shoulder, it causes the foot of the rafter to slide along the beam till the heel of the tenon bears against the outer end of the mortise.* This abutment is perpendicular to the beam in Price's book, but it is more generally pointed a little outwards below, to make it more secure against starting. The consequence of this construction is, that when the roof settles, the shoulder comes to

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* Price's *British Carpenter*, 4to. London.

bear at the inner end of the mortises, and it rises at the outer, and the tenon taking hold of the wood beyond it, either tears it out or is itself broken. This joint therefore is seldom trusted to the strength of the mortise and tenon, and is usually secured by an iron strap, which lies obliquely to the beam, to which it is bolted by a large bolt quite through, and then embraces the outside of the rafter foot. Very frequently this strap is not made sufficiently oblique, and we have seen some made almost square with the beam. When this is the case, it not only keeps the foot of the rafter from flying out, but it binds it down. In this case, the rafter acts as a powerful lever, whose fulcrum is the inner angle of the shoulder, and then the strap never fails to cripple the rafter at the point. All this can be prevented only by making the strap very long and very oblique, and by making its outer end (the stirrup part) square with its length, and making a notch in the rafter foot to receive it. It cannot now cripple the rafter, for it will rise along with it, turning round the bolt at its inner end. We have been thus particular on this joint, because it is here that the ultimate strain of the whole roof is exerted, and its situation will not allow the excavation necessary for making it a good mortise and tenon.

Similar attention must be paid to some other straps,* such as those which embrace the middle of

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* Tredgold's *Carpentry*, pp. 172, 192.

the rafter, and connect it with the post or truss below it. We must attend to the change of shape produced by the sagging of the roof, and place the strap in such a manner as to yield to it by turning round its bolt, but so as not to become loose, and far less to make a fulcrum for any thing acting as a lever. The strains arising from such actions, in framings of carpentry which change their shape by sagging, are enormous, and nothing can resist them.

37. We shall close this part of the subject with a simple method, by which any carpenter, without mathematical science, may calculate with sufficient precision the strains or thrusts which are produced on any point of his work, whatever be the obliquity of the pieces.

Let it be required to find the horizontal thrust acting on the tie-beam AD of Fig. 18. This will be the same as if the weight of the whole roof were laid at G on the two rafters GA and GD. Draw the vertical line GH. Then, having calculated the weight of the whole roof that is supported by this single frame ABCD, including the weight of the pieces AB, BC, CD, BE, CF, themselves, take the number of pounds, tons, &c. which expresses it from any scale of equal parts, and set it from G to H. Draw HK, HL, parallel to GD, GA, and draw the line KL, which will be horizontal when the two sides of the roof have the same slope. Then ML measured on the same scale will give the horizontal thrust, by which the strength of the tie-beam is to be regulated. GL will give the thrust which tends to crush the rafters, and LM will also give the force which tends to crush the strut-beam BC.

In like manner, to find the strain on the king-post BD of Fig. 17, consider that each brace is pressed by half the weight of the roofing laid on BA or BC, and this pressure, or at least its hurtful effect, is diminished in the proportion of BA to DA, because the action of gravity is vertical, and the effect which we want to counteract by the braces is in a direction E *e* perpendicular to BA or BC. But as this is to be resisted by the brace *f* E acting in the direction *f* E, we must draw *f e* perpendicular to E *e*, and suppose the strain augmented in the proportion of E *e* to E *f*.

Having thus obtained in tons, pounds, or other measures, the strains which must be balanced at *f* by the cohesion of the king-post, take this measure from the scale of equal parts, and set it off in the directions of the braces to G and H, and complete the parallelogram G *f* HK; and *f* K measured on the same scale will be the strain on the king-post.

38. The builder may then examine the strength of his truss upon this principle, that every square inch of oak will bear at an average 7000 pounds compressing or stretching it, and may be safely loaded with 3500 for any length of time; and that a square inch of fir will in like manner securely bear 2500. And, because straps are used to resist some of these strains, a square inch of well wrought tough iron may be safely strained by 50,000 pounds. But the student will

always recollect, that we cannot have the same confidence in iron as in timber. The faults of this last are much more easily perceived; and when timber is too weak, it gives us warning of its failure, by yielding sensibly before it breaks. This is not the case with iron; and much of its service depends on the manufacture of the iron.

39. In this way may any design of a roof be examined. We shall here give the reader a sketch of two or three trussed roofs, which have been executed in the chief varieties of circumstances which occur in common practice.

Fig. 39 in the previous volume *on Carpentry*, is the roof of St. Paul's Church, Covent Garden, London, the work of Inigo Jones. Its construction is singular. The roof extends to a considerable distance beyond the building, and the ends of the tie-beams support the Tuscan cornice, appearing like the mutules of the Doric order. Such a roof could not rest on the tie-beam. Inigo Jones has therefore supported it by a truss below it; and the height has allowed him to make this extremely strong with very little timber. It is accounted the highest roof of its width in London. But this was not difficult, by reason of the great height which its extreme width allowed him to employ without hurting the beauty of it by too high a pitch. The supports, however are disposed with judgment.*

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* See the previous volume *on Carpentry*.

Fig. 21.

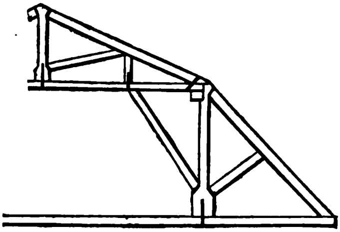
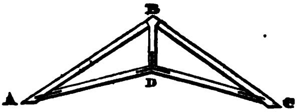


Fig. 21. is a kirb or mansard roof by Price, and supposed to be of large dimensions, having braces to carry the middle of the rafters.

It will serve exceedingly well for a church having pillars. The middle part of the tie-beam being taken away, the strains are very well balanced, so that there is no risk of its pushing aside the pillars on which it rests.

Fig. 22. is the celebrated roof of the theatre of the university of Oxford, by Sir Christopher Wren. The span between the walls is 75 feet. This is accounted a very ingenious, and is a singular performance. The middle part of it is almost unchangeable in its form; but from this circumstance it does not distribute the horizontal thrust with the same regularity as the usual construction. The horizontal thrust on the tie-beam is about twice the weight of the roof, and is withstood by an iron strap below the beam, which stretches the whole

FIG. 24.



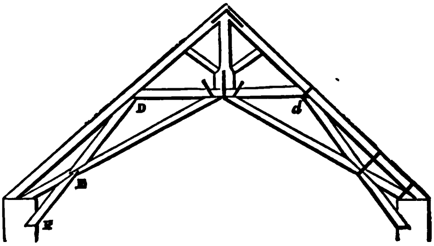
if we substitute a king-post BD (Fig. 24.) and two stretchers or hammer beams DA, DC, for the other strings, and connect them firmly by means of iron straps, we obtain our purpose.

Let us compare this roof with a tie-beam roof in point of strain and strength. Recur to Fig. 23. and complete the parallelogram ABCF, and draw the diagonals AC, BF, crossing in E. Draw BG perpendicular to CD. We have seen that the weight of the roof, (which we may call W,) is to the horizontal thrust at C as BF to EC; and if we express this thrust by T, we have $T = \frac{W \times EC}{BF}$. We may at present consider BC as a lever moveable round the joint B, and pulled at C in the direction EC by the horizontal thrust, and held back by the string pulling in the direction CD. Suppose that the forces in the directions EC and CD are in equilibrio, and let us find the force S by which the string CD is strained. These forces must (by the property of the lever) be inversely as the perpendiculars drawn from the centre of motion on the lines of their direction. Therefore BG : BE = T : S, and $S = T \times \frac{BE}{BG}, = W \times \frac{BE.EC}{BF.BG}$.

Therefore the strain upon each of the ties DA and DC is always greater than the horizontal thrust or the strain on a simple tie-beam. This would be no great inconvenience, because the smallest dimensions that we could give to these ties, so as to procure sufficient fixtures to the adjoining pieces, are always sufficient to withstand this strain. But although the same may be said of the iron straps which make the ultimate connections, there is always some hazard of imperfect work, cracks or flaws, which are not perceived. We can judge with tolerable certainty of the soundness of a piece of timber, but cannot say so much of a piece of iron. Moreover, there is a prodigious strain excited on the king-post, when BG is very short in comparison of BE, namely, the force compounded of the two strains S and S on the ties DA and DC.

But there is another defect from which the straight tie-beam is entirely free. All roofs settle a little. When this roof settles, and the points B and D descend, the legs BA, BC, must spread further out, and thus a pressure outwards is excited on the walls. It is seldom, therefore, that this kind of roof can be executed in this simple form, and other contrivances are necessary for counteracting this supervening action on the walls. Fig. 25. is a good example of the kind, and is executed

Fig. 25.



with great success in the circus or equestrian theatre in Edinburgh, the width being 60 feet. The pieces EF and ED help to take off some of the weight, and by their greater uprightness they exert a smaller thrust on the walls. The beam D *d* is also a sort of truss-beam, having something of the same effect. Mr. Price in his work on Carpentry has given another very judicious one of this kind, from which the tie-beam may be taken away, and there will remain very little thrust on the walls.

41. It is scarcely necessary to remind the reader, that in all that we have delivered on this subject, we have attended only to the construction of the principal rafters or trusses. In small buildings all the rafters are of one kind ; but in great buildings the whole weight of the covering is made to rest on a few principal rafters, which are connected by beams placed horizontally, and either mortised into them or scarfed on them. These are called *purlins*. Small rafters are laid from purlin

to purlin; and on these the laths for tiles, or the skirting boards for slates, are nailed. Thus the covering does not immediately rest on the principal frames. This allows some more liberty in their construction, because the attics can be so divided that the principal rafters shall be in the partitions, and the rest left unincumbered. This construction is so far analogous to that of floors which are constructed with girders, binding, and bridging joists.

It may appear presuming in us to question the propriety of this practice. There are situations in which it is unavoidable, as in the roofs of churches, which can be allowed to rest on some pillars. In other situations, where partition walls intervene at a distance not too great for a stout purlin, no principal rafters are necessary, and the whole may be roofed with short rafters of very slender scantling. But in a great uniform roof, which has no intermediate supports, it requires at least some reasons for preferring this method of carcase roofing to the simpler method of making all the rafters alike. The method of carcase-roofing requires the selection of the greatest logs of timber, which are seldom of equal strength and soundness with thinner rafters. In these the outside planks can be taken off, and the best part alone worked up. It also exposes to all the defects of workmanship in the mortising of purlins, and the weakening of the rafters by this very mortising; and it brings an additional load of purlins and short rafters. A roof thus constructed may surely be compared with a floor of similar construction. Here there is not a shadow of doubt, that if the girders were sawed into planks, and these planks laid as joists sufficiently near for carrying the flooring boards, they will have the same strength as before, except so much as is taken out of the timber by the saw. This will not amount to one-tenth part of the timber in the binding, bridging, and ceiling joists, which are an additional load; and all the mortises and other joinings are so many diminutions of the strength of the girders; and as no part of a carpenter's work requires more skill and accuracy of execution, we are exposed to many chances of imperfection. But, not to rest on these considerations, however reasonable they may appear, we shall relate an experiment made by one on whose judgment and exactness we can depend.

42. Two models of floors were made 18 inches square of the finest uniform deal, which had been long seasoned. The one consisted of simple joists, and the other was framed with girders, binding, bridging, and ceiling joists. The plain joists of the one contained the same quantity of timber with the girders alone of the other, and both were made by a most accurate workman. They were placed in wooden trunks 18 inches square within, and rested on a strong projection on the inside. Small shot was gradually poured in upon the floors, so as to spread uniformly over them. The plain joisted floor broke down with 487 pounds, and the carcase floor with 327. The first broke without giving any warning;

the other gave a violent crack when 294 pounds had been poured in.

A trial had been made before, and the loads were 341 and 482. But the models having been made by a less accurate hand, it was not thought a fair specimen of the strength which might be given to a carcase floor.

The only argument of weight which we can recollect in favour of the compound construction of roofs is, that the plain method would prodigiously increase the quantity of work, would admit nothing but long timber, which would greatly add to the expence, and would make the attics a mere thicket of planks. We admit this in its full force; but we continue to be of the opinion that plain roofs are greatly superior in point of strength, and therefore should be adopted in cases where the great difficulty is to insure this necessary circumstance.

43. It would appear very neglectful to omit an account of the roofs put on round buildings, such as domes, cupolas, and the like. They appear to be the most difficult tasks in the art of carpentry. But the difficulty lies entirely in the mode of framing. It is plain, that whatever form of a truss is excellent in a square building must be equally so as one of the frames of a round one; and the only difficulty is how to manage their mutual intersections at the top. Some of them must be discontinued before they reach that length, and common sense will teach us to cut them short alter-

nately, and always leave as many, that they may stand equally thick as at their first springing from the base of the dome. Thus the length of the purlins which reach from truss to truss will never be too great.

The truth is, that a round building which gathers in at top, like a glasshouse, a potter's kiln, or a spire steeple, instead of being the most difficult to erect with stability, is of all others the easiest.* Nothing can show this more forcibly than daily practice, where they are run up without centres and without scaffoldings: and it requires gross blunders indeed in the choice of their outline to put them in much danger of falling from a want of equilibrium. In like manner, a dome of carpentry can hardly fall, give it what shape or what construction you will. It *cannot* fall unless some part of it flies out at the bottom: an iron hoop round it, or straps at the joinings of the trusses and purlins, which make an equivalent to a hoop, will effectually secure it. And as beauty requires that a dome shall spring almost perpendicularly from the wall, it is evident that there is hardly any thrust to force out the walls. The only part where this is to be guarded against is, where the tangent is inclined about 40 or 50 degrees to the horizon. Here it will be proper to make a course of firm horizontal joinings.

We doubt not but that domes of carpentry will now be raised of great extent. The old Halle au Bled at

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* See Tredgold's *Carpentry*, 4to., plates, 36-38.

Paris, of 200 feet in diameter, was the invention of an intelligent carpenter, the Sieur Moulineau. He was not by any means a man of science, but had much more mechanical knowledge than artisans usually have, and was convinced that a very thin shell of timber might not only be so shaped as to be nearly in equilibrio, but that if hooped or firmly connected horizontally, it would have all the stiffness that was necessary; and he presented his project to the magistracy of Paris. The grandeur of it pleased them, but they doubted of its possibility. Being a great public work, they prevailed on the Academy of Sciences to consider it. The members, who were competent judges, were instantly struck with the justness of Mr. Moulineau's principles, and were astonished that a thing so plain had not been long familiar to every house-carpenter. It quickly became an universal topic of conversation, dispute, and cabal, in the polite circles of Paris. But the Academy having given a very favourable report of their opinion, the project was immediately carried into execution, and soon completed. It is now replaced by one of smaller dimensions erected with ribs of iron covered with sheets of copper.

The construction of this dome was the simplest thing that can be imagined. The circular ribs which composed it consisted of planks nine feet long, 13 inches broad, and three inches thick; and each rib consisted of three of these planks bolted together in such a manner that two joints meet. A rib was begun, for instance, with a plank of three feet long standing between one of six feet and another of nine, and this is continued to the head of it. No machinery was necessary for carrying up such small pieces, and the whole went up like a piece of bricklayer's work. At various distances these ribs were connected horizontally by purlins and iron straps, which made so many hoops to the whole. When the work had reached such a height, that the distance of the ribs was two-thirds of the original distance, every third rib was discontinued, and the space was left open and glazed. When carried so much higher that the distance of the ribs is one-third of the original distance, every second rib (now consisting of two ribs very near each other) is in like manner discontinued, and the void is glazed. A little above this the heads of the ribs are framed into a circular ring of timber, which forms a wide opening in the middle; over which is a glazed canopy or umbrella, with an opening between it and the dome for allowing the heated air to get out.

The only difficulty which occurs in the construction of wooden domes is, when they are unequally loaded, by carrying a heavy lanthern or cupola in the middle.* In such a case, if the dome were a mere shell, it would be crushed in at the top, or the action of the wind on the lanthern might tear it out of its place. Such a dome must therefore consist of trussed frames. Mr. Price has given a very good example, though much

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* Tredgold's *Carpentry*, 4to., pp. 116-118.

stronger in the trusses than there was any occasion for. This causes a great loss of room, and throws the lights of the lanthern too far up. It is evidently copied from Sir Christopher Wren's dome of St. Paul's church in London; a model of propriety in its particular situation, but by no means a general model of a wooden dome. It rests on the brick cone within it; and Sir Christopher has very ingeniously made use of it for stiffening this cone, as any intelligent person will perceive by attending to its construction.

FIG. 26.

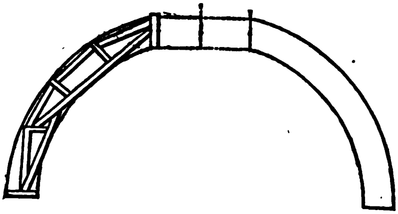


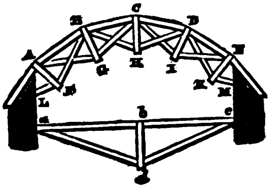
Fig. 26. represents a dome executed in the Register Office of Edinburgh, by James and Robert Adam, and is very agreeable to mechanical principles. The span is 50 feet clear, and the thickness is only 4½.

44. We cannot quit this subject without taking some notice of what we have already spoken of with commendation by the name of *Norman roofs*. We called them *Norman*, because they were frequently executed by that people soon after their establishment in Italy

and other parts of the south of Europe, and became the prevailing taste in all the great baronial castles. Their architects were rivals to the Saracens and Moors, who about that time built many Christian churches; and the architecture which we now call Gothic seems to have arisen from their joint labours.

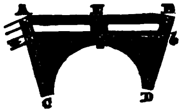
The principle of a Norman roof is extremely simple. The rafters all butted on joggled king-posts AF, BG, CH, &c. (Fig. 27.), and braces or ties were then disposed in the intervals. In the middle of the roof HB and HD are evidently ties in a state of extension, while the post CH is compressed by them. Towards the walls on each side, as between B and F, and between F and L, they are braces, and are compressed. The ends of the posts were generally ornamented with knots of flowers, embossed globes, and the like, and the whole texture of the truss was exhibited and dressed out.

Fig. 27.



This construction admits of employing very short timbers; and this very circumstance gives greater strength to the truss, because the angle which the brace or tie makes with the rafter is more open. We may also perceive that all thrust may be taken off the walls. If the pieces AF, BF, LF, be removed, all the remaining diagonal pieces act as ties, and the pieces directed to the centre act as struts; and it may also be observed, that the principle will apply equally to a straight or flat roof, or to a floor. A floor such as *a b c*, having the joint in two pieces *a b*, *b c*, with a strut *b d*, and two ties, will require a much greater weight to break it than if it had a continued joist *a c* of the same scantling. And, lastly, a piece of timber acting as a tie is much stronger than the same piece acting as a strut: for in the latter situation it is exposed to bending, and when bent it is much less able to withstand a very great strain. It must be acknowledged, however, that this advantage is balanced by the great inferiority of the joints in point of strength. The joint of a tie depends wholly on the pins; for this reason ties are never used in heavy works without strapping the joints with iron. In the roofs we are now describing, the diagonal pieces of the middle part only act purely as ties, while those towards the sides act as struts or braces. Indeed they are seldom of so very simple construction as we have described, and are more generally constructed like the sketch in Fig. 28. having two sets of rafters AB, *a b*, and the angles are filled up with thin planks, which give great stiffness and strength. They have also a double set of purlins, which connect the different trusses. The roof being thus divided into squares, other purlins run between the middle points E of the rafters. The rafter

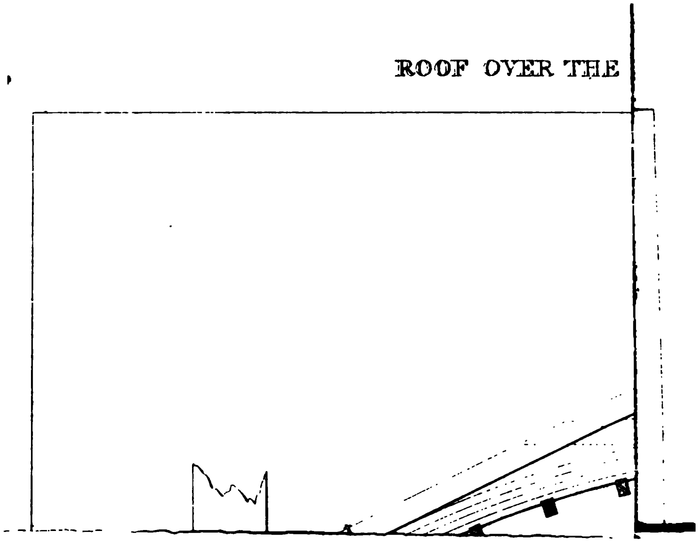
FIG. 28.



is supported at E by a check put between it and the under rafter. The middle point of each square of the roof is supported and stiffened by four braces, one of which springs from *e*, and its opposite from the similar part of the adjoining truss. The other two braces spring from the middle points of the lower purlins, which go horizontally from *a* and *b* to the next truss, which are supported by planks in the same manner as the rafters. By this contrivance the whole becomes very stiff and strong.

45. We hope that the reader will not be displeased with our having taken some notice of what was the pride of our ancestors, and constituted a great part of the finery of the grand hall, where the feudal lord assembled his vassals, and displayed his magnificence. The intelligent mechanic will see much to commend; and all who look at these roofs admire their apparent flimsy lightness, and wonder at their duration. We have seen a hall of 57 feet wide, the roof of which was in fou divisions, like a kirb roof, and the trusses were abou 16 feet asunder. They were single rafters, as in Fig 28. and their dimensions were only eight inches by six

ROOF OVER THE



The roof appeared perfectly sound, and had been standing ever since the year 1425.

46. Much of what has been said on this subject may be applied to the construction of wooden bridges, and the centres for turning the arches of stone bridges.

47. *Roof at Charter-House.* Fig. 29. The roof at Charter-House is formed with circular ribs in four thicknesses of 1½ in. deal four inches wide, with saw cuts half an inch in depth on the under sides, and put together with *marine glue*, on a cradle centre. The dotted lines shew the collars, which are dove-tailed one inch into the sides of the principal rafters. The principal rafters, being five inches wide, project on one side an inch before the face of the circular ribs, which are only four inches wide. On the collars rest the purlins supporting the rafters. The ceiling joists are spiked up to the circular ribs. Wall plates in old wall 4 in. by 2½ in.; lower plate in new wall. 5 in. by 2½ in.; upper plate 6 in. by 4 in. Five circular ribs 6 in. by 4 in., bent in four thicknesses; purlins 5 in. by 4 in. Collars 6 in. by 2 in.; rafters 4 in. by 2½ in.; ceiling joist 3 in. by 2 in.

48. *Roof of Clerkenwell Church.* Fig. 30. Early in the year 1843 it was discovered that a portion of the ceiling, near the South-East corner of Saint James' Church, Clerkenwell, had sunk down about five inches. On examination, it was found that the ends of the tie-beams were much decayed from dry rot, as were also the ends of the principal rafters.

The tie-beams were scarfed with dry fir timber and three iron ties 3 in. by ¾ in. on the top and bottom, bolted together. The iron shoe, with its three bearers, was in one casting ¾ of an inch in thickness; the bearers of the shoe resting on the upper iron ties, which were turned up and down at the ends one inch. Oak wedges were used between the notched ends of the principal rafters and the cast-iron shoe, and the long bolt put in to connect the principal rafters with the tie-beam. The whole was then screwed up to the original level.

Edward M. Barry, Esq., Architect, of Westminster, has kindly added to the value of our work by contributing drawings of the very recently constructed roof of the Leeds Grammar School, erected by him this year, of which the following is an account, with illustrations of the same. I have also to bring the subject of modern iron roofs before the practical builder by the publication of several examples in an Atlas, 4to. size, sold to accompany, with or without this little volume.

49. *Leeds Grammar School, erected* 1859. Figs. 31, 32, 33, and 34. The roof is over the principal school-room, and consists of 6 bays 16 feet wide, each bay containing a dormer. The main trusses have arched ribs resting in stone corbels, and in the centre of each bay is an intermediate truss without arched ribs. The collar beam of the intermediate truss forms the ridge of the roofs of dormers, and is in one continuous piece from wall to wall. The wood is Memel fir, and is stuccoed and varnished. The span and scantlings of timbers [illegible] *follows* over leaf:—

Span	28 feet.
Width of bay	16 feet.
Principal rafters	9 in. × 6 in.
Common rafters	3½ in. × 2½ in.
Fillets under battens	2 in. × 1½ in.
Arched ribs	4 in. thick.
Ridge	6 in. × 4 in.
Collar	9 in. × 6 in.

[*For Diagrams* 31—34 *see following leaves* 96—101.]

FIG. 31.

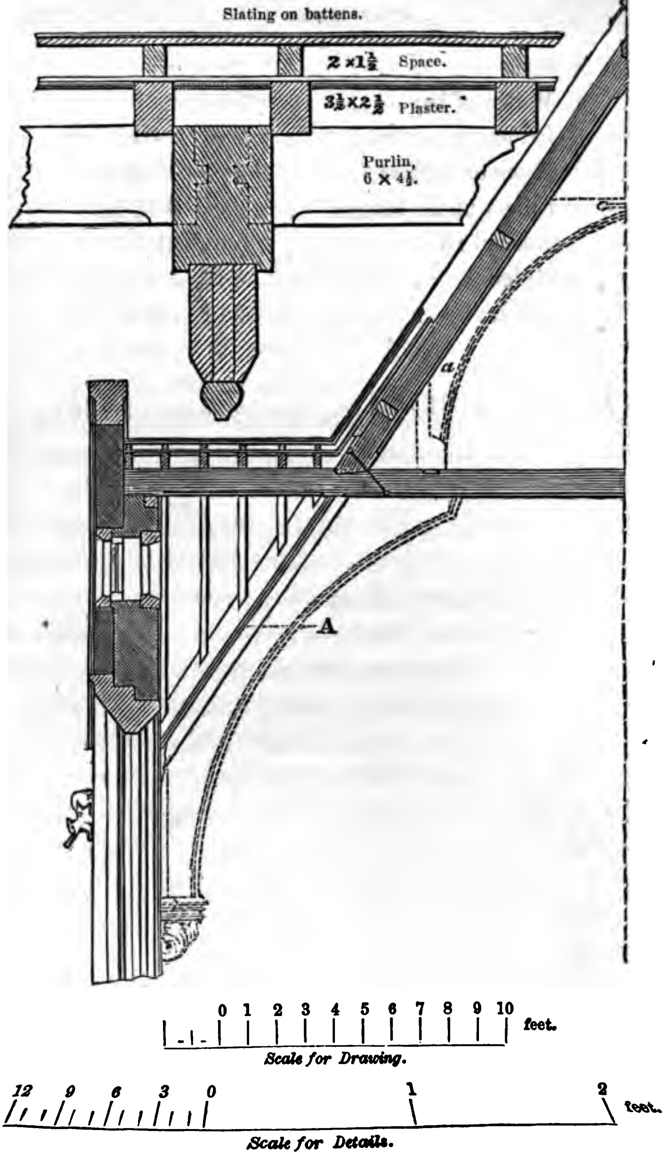

Slating on battens.
2 × 1½ Space.
3½ × 2½ Plaster.
Purlin,
6 × 4½.
a
A
0 1 2 3 4 5 6 7 8 9 10 feet.
Scale for Drawing.
12 9 6 3 0 1 2 feet.
Scale for Details.

FIG. 32.

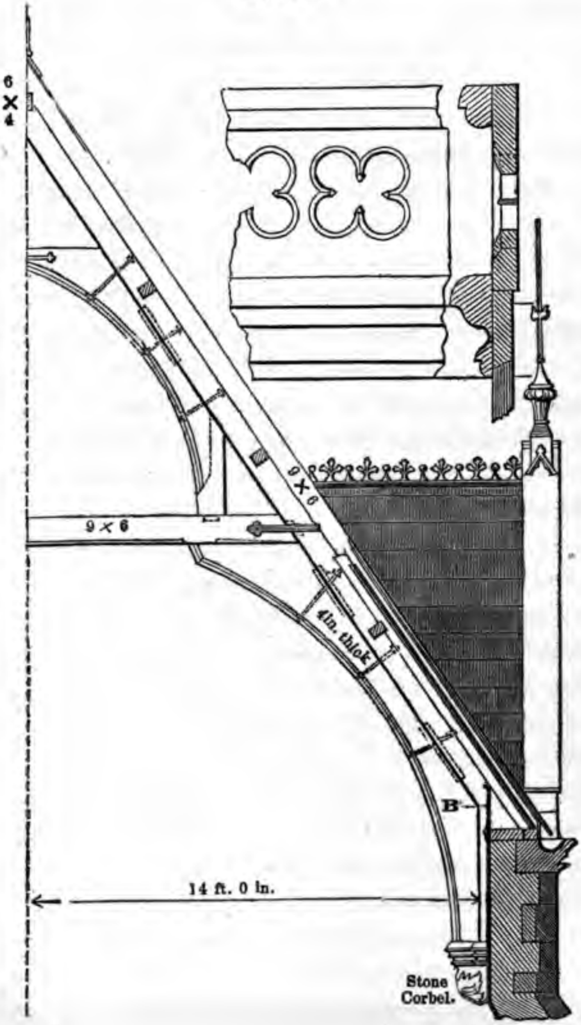


FIG. 33.

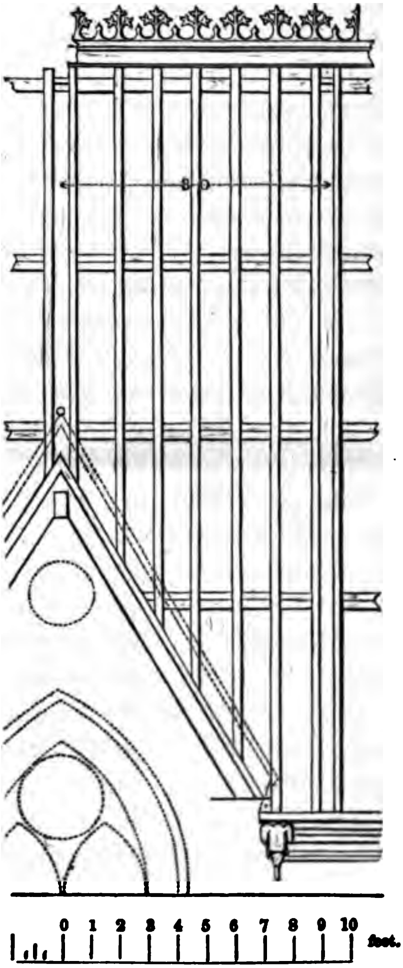
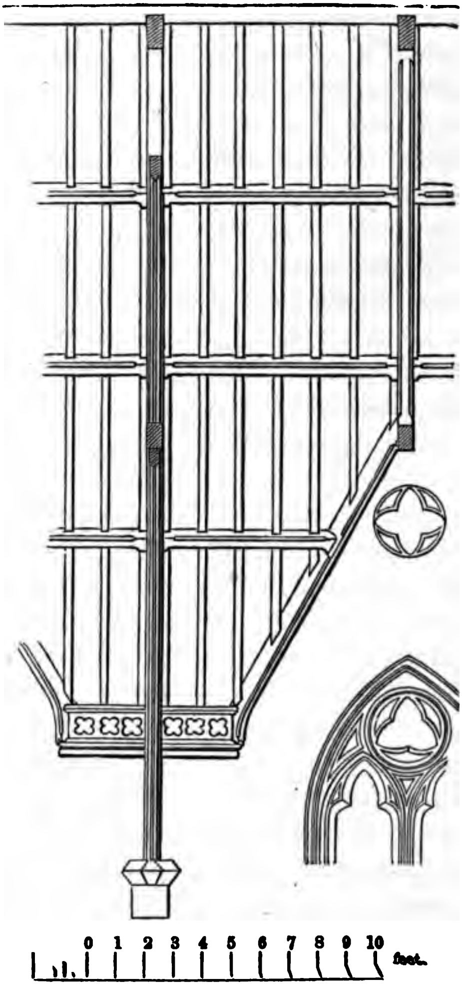


Fig. 34.



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