<u>MULTI-PLATE ARMOR VERSUS SINGLE SOLID PLATES:</u>
<u>PROS AND CONS FOR EACH</u>
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This question has several parts, based on (1) the method of resistance of the armor to penetration, including geometric considerations at oblique impact, (2) the damage inflicted on the projectile attempting to penetrate the armor, and (3) structural ship design considerations for the support for the armor and its distribution.

I. Plate Resistance Effects.

A. The Three Basic Types of Resistance.

There are three extremes of plate resistance. In most cases a real plate is somewhere in-between the extremes, though in some cases the approximation of one of the extremes is quite close to the actual observed effects.

1. *Trampoline Effect Rule.* The first extreme is only applicable to very thin (under 0.1-caliber (projectile diameter) thickness) highly ductile (easily bent and stretched) homogeneous (same everywhere) armor or construction steels. Here the plate acts like a trampoline and stretches over a wide area around the impact point, termed "dishing". The thinner the plate, the wider this region becomes until in extremely thin plates (under 0.01 caliber or so), the entire plate is involved. Thus, as the plate thickness T gets thinner and thinner in this narrow low-end range, the energy required to penetrate it per unit thickness actually INCREASES rapidly, roughly as the inverse of the increasing volume of armor adding itself to the resistance, KE needed/unit depth = $\sim KV^2/T^3$, for some constant of resistance K and striking velocity V. This drop bottoms out near the 0.05-caliber thickness value and then the resistance begins to rise faster and faster as thickness increases using the Linear Velocity Rule extreme described below. Above 0.1 caliber this dishing effect has dropped to only a slight modification of the total penetration resistance and is essentially gone by 0.25-caliber (the dishing area around the impact site has become more-or-less of a constant size and only by a shallow amount, so it is a constant energy absorption effect thrown in as part of the total energy needed to penetrate the plate, not as a separate factor). As indicated, this is only for very slowly-moving projectiles at near right-angle ("normal") impact, but is much more important at very highly oblique impacts where the projectile hits at high velocity and glances off of even rather thin plate (the reason for deck armor in the first place). This gradual denting as the projectile in a highly oblique impact moves forward keeps the force on the projectile's "chin" (nose touching the plate) and rotates it enough to, hopefully, cause it to begin to move up and away from the plate and glance off before it has dug deep enough to tear the tip of its nose through and peel the plate upward (forming what is called a "spur" on the far end of the dent where it suddenly becomes a caliber-wide hole), rather than previously downward, "ricocheting" into the space behind the armor at high speed. The plates of the Linear Velocity Rule for a pointed projectile are thick enough for this effect, too.

2. *Kinetic Energy Rule.* This is at the opposite plate thickness extreme for a ductile homogeneous plate being penetrated by an pointed or oval-nosed projectile (generally, if the nose is longer than it is wide and allows the plate material to move sideways out of the way), very thick plates over 1 caliber thick. The thicker the plate and the more pointed the projectile nose, the closer it comes to this approximation, though conventional projectiles can never remain intact at the high-enough velocities to make this approximation really close (over 2-caliber-thick plate); for this approximation to be true, you have to study narrow fin-stabilized long rod penetrators punching though very thick armor by essentially melting their way through. This method of penetration is much like swimming in water (imagine the projectile as if it were a torpedo passing through the target as if it were water), with the material behind the projectile or in front of it not making any difference -- only the plate material it is pushing out of the way at the moment is involved in trying to stop the projectile. The depth of penetration in the ideal form would be $T = \sim KV^2$ or, assuming the projectile mass is part of K, the total kinetic energy (KE) of the projectile based on its impact velocity V. In this approximation, the armor is being wedged sideways only out of the projectile's path, bulging the plate in a ring around the impact site (the material in front of the projectile does not let the armor move forward at all) -- the cratering of the face and the bulging and tearing open of the back, forming bent-back teeth ("petals") ringing the hole, are ignored here as mere minor adjustments to the penetration resistance (they are important in the third extreme, the Linear Velocity Rule, below). Oblique impact is only possible at rather low obliquities if the striking velocity is to remain reasonable against such thick armor.

3. *Linear Velocity Rule.* In this case, the material in front of the projectile from the face to the back fails IN ONE PIECE by being force out of the projectile's path out the plate back, either as a cork-like plug or by being torn in the middle and folded back to the sides as thick petals, all as one solid piece of material the total plate thickness deep. This can be approximated by a flat-nosed projectile slicing out a disk of armor like a cookie cutter, but it also occurs in moderately-thick plates hit by pointed projectiles when the resistance is primarily by tearing open in the center over the tip of the point and wedging the hole open by petal-formation, that is, by pushing the plate material forward as it splits open in the center and then having it bend to the sides, since it is still attached to the armor ringing the impact site -- this is not the same thing as the sideways-only wedging in the Kinetic Energy Rule, where the material cannot move forward at all due to the material deeper into the plate preventing it. This situation has the formula $T = \sim KT$. This can be proved as follows: Assume that, like the cork in the bottle, the friction resistance along sides of the plug to be pushed out is constant everywhere (reasonable enough), so that the resistance force $F(r) = K(r)T$ for some constant $K(r)$. The energy called "Work" is the amount of distance moved against a resistance force, so Work = $K(r)TT = K(r)T^2$. for the plate thickness T -- or any fraction of T, actually, though here the plug will not move at all (it is assumed to be incompressible) until the applied force is greater than F(r) and thus allows the entire plug to move as one piece. The KE available for this Work is the projectile motion energy KE = (0.5)(Projectile Mass M)V^2, so to barely penetrate the plate, they are equal: $(0.5)MV^2 = K(r)T^2$ and this simplifies down to $T = [(0.5)M/K(r)]V$, as required, with the above $K = (0.5)M/K(r)$. Bending back and tearing open T-thickness petals takes the same kind of full-plate-thickness resistance to be overcome before the

projectile can penetrate, so the rule is the same. Note that there is a maximum plate thickness before the plate material gets so rigid that the material finds it easier to move sideways than to be pushed forward, with this being about 0.5-caliber thickness, so when the thickness gets above this, the face beings to form a narrow, bulged-up crater ring around the impact site which gets up to about 0.25-caliber deep maximum, and when the plate gets about 0.75-caliber thick, the central Kinetic Energy Rule wedging region starts to grow, with all further thickness increases being in that central region, relegating the cratering to the 0.25-caliber-deep face layer and the torn open and folded-back petals to the 0.5-caliber-deep back layer. The change from the Linear Velocity Rule to the Kinetic Energy Rule as plate thickness continues to go up is thus rather gradual. At oblique impact, the plates that use the Linear Velocity Rule are thin enough to be able to tilt rather a lot and still have the chance of being penetrated at a reasonable velocity, so this is a major component of deck armor resistance, particularly WWII thick armor decks.

B. Effects of Divided Armor Using These Rules.

(1) *Kinetic Energy Rule.* For plates that follow this rule closely, there is little to gain from using a solid plate versus parallel spaced thinner plates or two or more thinner laminated plates (separate plates bonded together) of the same total weight. This can be seen by the following: If it takes 1000 ft/sec to penetrate a 1-inch plate that follows the KE Rule, then if they are spaced, you need the energy to penetrate the first of, say, two plates with the projectile exiting the first one (assumed undamaged and still moving point-first) at 1000 ft/sec to barely be able to penetrate the second one. The total energy needed when hitting the first plate to do this is:

$$\begin{gathered} KE(\#1+\#2) - KE(\#1) = KE(\#2) \\ KV^2 - K(1000)^2 = K(1000)^2 \\ V^2 = 2(1000)^2 \\ V = 1000[\text{Square-Root of } 2] \\ V = 1414.214 \text{ ft/sec} \end{gathered}$$

but this is the exact same velocity needed to penetrate a solid 2-inch plate that follows this rule: 2-inch = $KV^2 = K(1414.214)^2 = (2)K(1000)^2$ = (2)(1-inch plate). ***Thus, with plates that follow the KE Rule, spacing of two or more plates, laminating two or more plates, or making one thick plate, in any combination, makes no difference as to direct projectile penetration through the entire armor array, if parallel plates are used (at low obliquity, at least).***

(2) *Linear Velocity Rule.* For plates using this rule, the total energy needed for a pair of 1-inch spaced plates follows the exact same logic as in the KD Rule explanation above, so that for two parallel spaced 1-inch plates that take 1000 ft/sec each, the total energy needed would give a striking velocity of 1414.214 ft/sec, just as above. However, if you fused the two plates into one solid 2-inch plate, it needs 2,000 ft/sec to penetrate, so that spacing the plates causes a really big loss in protection. This is because the material in the first plate is totally independent of the second plate and only has half the side resistance before starting to be cut out of the first plate and only has to move half as far (1

inch instead of 2 inches) before being completely free of the first plate (if a plug) or bent out of the projectile's way (if petals) and knocked aside by the projectile as it moves toward the second plate, which repeats these results, though with the projectile barely falling out of its back at near zero remaining speed. If the plates were laminated together by being bonded into something similar to a solid plate, the laminated array would more closely follow the Linear Velocity Rule, though if the plates could dish and bend separately, the first plate could still be torn through prior to the second plate being subject to its maximum force from the projectile, as transmitted through the plug/petals just made in the first plate. Since that first-plate plug/petals is/are riding the nose of the projectile, it/they must be pushed through the second plate too (except for some first-plate material that can be pushed sideways into the crack between the plates) before the projectile can get through the second plate, so the resistance is considerably higher than if the two thinner plates were spaced far apart. If plugs were formed here and these plugs were absolutely rigid, then there would be almost no difference between the laminated case and the solid plate case, but this is not true with real steel plate materials. ***Thus, with plates that follow the Linear Velocity Rule (and ignoring any other effects on the projectile due to the impact at the moment), using anything but single solid plates is clearly inferior to the single solid plate case, with the laminated case varying in its amount of reduction depending on the materials used (I usually spit the difference between the solid plate and the spaced plate cases when I calculate the laminated case, which works for most ductile plates that can form petals or plugs depending on the projectile nose shape and impact obliquity).***

(3) *Trampoline Effect Rule*. If you needed thin armor, this would be the way to go if you had enough room to allow wide-enough spacing between the parallel plates to prevent them from compromising their denting action and could afford the cost of making and supporting so many thin plates to build up the total resistance to what you want. Making these spaced plate non-parallel to optimize against projectiles coming from known directions is also possible, though it might compromise the protection coming from another direction, of course. As this is usually not very practical, the armor using this rule is rarely made against projectiles. However, against large underwater detonations with the powerful, but very blunt "water hammer" blast effect on plates, this rule is used with good effect in large warship side protection systems against torpedoes, incorporating in the more successful designs deep liquid-filled spaces between most of the individual plates to soak up the water hammer's energy and to spread the force over a wide area that must be torn to open at each successive layer of the protection system. ***Thus, with plates that follow this rule, several widely-spaced armor plates against small or slow-moving projectiles would be significantly stronger than solid plates of the same total weight, assuming the weight of the supporting structure to hold these plates does not nullify this gain. The plates following this rule are significantly more effective at highly oblique angles when the deflection of the projectile from its original course is not too great after penetrating each layer.***

C. Real Plates.

Real armor hit by real projectiles usually does not act as these extremes.

Other than very thin plates hit by projectiles at very high obliquities, projectiles are usually moving too fast for the Trampoline Effect Rule to have much use (only if the projectile punches through an armor plate in more-or-less an intact condition inside a large warship and bounces round a number of times will it slow itself down enough for this effect to be useful and in most cases the projectile fuze will have detonated it by then. The Kinetic Energy Rule is always used to add spaced plates in that the energy remaining after penetration of a given plate is changed into a Remaining Velocity and this is used as the Impact Velocity on the next plate in line. If the projectile is deflected or damaged by the plate, some method is needed to account for this before calculating what happens to the next plate.

As the striking velocity increases above the minimum to barely penetrate, the projectile and plate may change how much each absorbs during the penetration process. For example, if the plate has a plug punched out, the plug must move fast enough to be ahead of the projectile nose. It thus soaks up more and more energy as it has to accelerate more and more to do so. This energy is supplied by the projectile, so the projectile has that much less extra energy after it penetrates (this gets especially complicated if the plug and the projectile are not moving in the same direction after an oblique impact). Also, the projectile may deform or, at a high-enough velocity, shatter. These will cause the projectile to absorb a significantly higher amount of energy than when it barely penetrated. In the case of shatter, the loss of energy due to the damage may be so great that the projectile stops penetrating until the velocity is raised to a much higher value where its pieces can penetrate anyway, creating a "shatter gap" where penetration cannot occur, even though it occurs both below (unshattered, possibly completely intact) and above this gap (shattered usually into many pieces) -- British 2-pdr. AP shot shattered in this manner against specially modified German tanks with thin, spaced, hardened plates in front of their regular armor during the Battles in North Africa in mid-WWII. Thus, spaced armor at near normal obliquity can have complicated effects as the plates do different things to the projectile that changes what the projectile does to all the plates hit later. Each plate penetration has to be calculated individually and the results then applied to the next plate in line, one at a time.

As to penetrating a given plate, most plates are in the 0.2-1.1-caliber thickness range so they could seem to be closer to the Linear Velocity Rule than the Kinetic Energy Rule. However, the shift at the low end of this thickness range from the Trampoline Effect Rule and the more gradual change at the high end toward the Kinetic Energy Rule cause the shape of the penetration-versus-projectile-energy curve to deviate noticeably from the simple Linear Velocity Rule in this range. What you get is kind of an "S"-shaped curve that only for a short interval near the 0.5-caliber thickness at normal has the ideal Linear Velocity Rule shape.

My M79APCLC program shows this exact curve shape (based on many US Naval Proving Ground tests averaged for narrow intervals over this range, as well as for impacts up to 2.0-caliber thickness and down to 0.01-caliber thickness) if you plot penetration in calibers (horizontal scale) versus projectile impact energy per unit plate thickness in calibers to barely penetrate (that is, plot KE/(T/D) vertically versus T/D horizontally), where D is the projectile diameter (nominal gun bore for most conventional projectiles) over the T/D value range of 0.2-1.1.

The French DeMarre Nickel-Steel Armor Penetration Formula of 1890, when matched by choosing a DeMarre Coefficient (C) at normal obliquity that exactly matches the M79APCLC results at 1.0 caliber plate thickness (C = 1.21 works pretty well), intertwines with my M79APCLC curve even though it has a single exponential for the V (actually for the projectile KE = $(0.5)MV^2$). This exponent is 1/1.4 = 0.7142857, so the V exponent is (2)(0.7142857) = 1.42857 and the formula for armor penetration becomes $T = \sim KV^{1.42857}$. This value is very close to the center between 1.0 for the Linear Velocity Rule and 2.0 for the Kinetic Energy Rule. Thus, actual homogeneous armor acts like a middle ground between these two extreme rules over the usual range of plate thicknesses on warships (against the weapons they were designed for -- cruisers are not armored against battleship ammunition!). Since it gives roughly the same results as M79APCLC does when properly calibrated for that one common point (1.0-caliber plate), obviously homogeneous ductile armor is indeed close to the middle between the extremes as to how the plate fails due to a typical bluntly-pointed projectile. Thus, if this formula is used in approximations of various penetration processes over the typical plate thickness range given, the results will be pretty close to the "ballpark" center. This is convenient, since the M79APCLC results vary for each projectile and do not follow a constant curve shape, so it is more difficult to determine this center value from it -- the DeMarre Formula is easier to use.

Conversely, we have $V = \sim[T/K]^{(1/1.42857)} = \sim[T/K]^{0.7} = \sim K'T^{0.7}$.

Since the Kinetic Energy Rule is used for adding N spaced parallel armor plates hit at near normal obliquity (if no deflection or projectile damage as the projectile passes through the array), we have

$$\text{KE(total needed to barely penetrate)} = \text{KE(Plate \#1)} + \text{KE(Plate\#2)} + \ldots + \text{KE(Plate \#N)}$$
$$KV^2 = KV(\#1)^2 + KV(\#2)^2 + \ldots + KV(\#N)^2$$
$$(K')^2[T^{0.7}]^2 = (K')^2[T(\#1)^{0.7}]^2 + (K')^2[T(\#2)^{0.7}]^2 + \ldots + (K')^2[T(\#N)^{0.7}]^2$$
$$T^{1.4} = T(\#1)^{1.4} + T(\#2)^{1.4} + \ldots + T(\#N)^{1.4}$$
$$\text{T(entire spaced array)} = [T(\#1)^{1.4} + T(\#2)^{1.4} + \ldots + T(\#N)^{1.4}]^{0.7142857}$$

as long as the all of the T(#N) plates are in the 0.2-1.1-caliber thickness range. This is probably as good an approximation as you are likely to get for a "typical" average pointed projectile passing through these plates. You can calculate each plate in series, but this is only really necessary for much blunter noses shapes not using the DeMarre Formula or higher obliquities where the projectile may be deflected or for projectile damage .

D. Laminated Plate Formulae.

Laminated plates are always parallel, which simplifies things. Also, they are tightly bound together so that to reach the later plates you have to punch through the earlier plates. This supports the earlier plates where they try to push material backward to get out of the projectile's path, since the later plates' material prevents that from moving back easily, if at all. Thus, the earlier plates end up resisting the projectile penetration simply due to the fact that their material that would usually be pushed out of the way is now partially trapped unless it wedges itself into the cracks between the plates or is physically pushed through the later plates by the force of the projectile's nose. Thus, resistance is greater than completely spaced plates, but less than a single solid plate, assuming, as we did above, that the DeMarre Formula is good enough for a rough average accounting for the resistance of the thick plate and for the resistance of each thinner plate, if it were spaced.

The US Navy after WWI, when determining the resistance of two laminated plates of the same type, simply assumed that the upper plate was reduced by 30% -- was only 70% as strong -- as to its thickness and then physically added to the complete thickness of the lower plate. For example, if the upper plate was 5" STS and the lower plate was 2" STS, the total effective deck thickness, regardless of the angle of impact or projectile type, was T(deck) = (0.7)(5) + 2 = 5.5" compared to 7" of total weight. This is quite a loss of strength for the weight, so there had better be a very good reason for not using a solid 7" plate. (There usually is, as will be discussed under structural considerations, below.)
If the plates were not the same type (nickel-steel under-plate with STS laid over it, for example), I think that rules-of-thumb plate thickness reductions for the nickel-steel plates before applying the 0.7 rule. Using the DeMarre Formula C = 1.21, the nickel-steel plate thickness should be reduced to $(1/1.21)^{1.42857}$ = 0.7616 times the actual thickness before applying the 0.7 rule. I tend to use a larger value, closer to 0.9, than 0.7616 resistance when adding laminated plates because nickel-steel may not be as strong under direct impact, but during the time it is supporting the STS plate prior to that plate being holed and the projectile directly penetrating the underlying nickel-steel plate, the nickel-steel plate is using its tensile and yield strengths and these are not that far below those of STS (the nickel-steel is more brittle and tears open easier, but is somewhat stronger as a backing plate under a more spread-out force passing through the upper STS plate).
My formula is to split the difference between the kinetic energy addition rule for N plates given above, using the DeMarre Formulae, and the simple addition of plate thicknesses, also applying plate quality factors first if mixed plates are used to make them all of a single STS-equivalent thickness. It is based on a large set of tests of US Army 0.5" AP machinegun bullets against plates of several thicknesses laminated together and hit at obliquities from normal to 70 degrees. Thus, in the 5" + 2" STS laminated array given above, I would use

$$T(\text{deck}) = \{(5'' + 2'') + [(5'')^{1.4} + (2'')^{1.4}]^{0.7142857}\}/2 = \{7'' + (12.1573)^{0.7142857}\}/2$$
$$T(\text{deck}) = (7'' + 5.96'')/2 = (12.96'')/2 = 6.48''$$

Note that I give the deck armor significantly more effective thickness than the US Navy itself did. Even the pure spaced armor (no support between plates) computation gives 5.96", which is greater than the US Navy value and the DeMarre Formula is known to be reasonably accurate, as mentioned above, at normal impact. Note also that if you reversed the layers, with the 2" on top of the 5", the US Navy formula gives 6.4", which is almost exactly what I give. Thus, it is possible that the order of the plate thicknesses makes a big difference in resistance of a laminated array, but none of my data indicates this to be true. It was not true for the tests I used to base my split-the-difference lamination formula (if it was I would have added it). The only thing I use concerning the order is that when adding the plates together, I use the metallurgical properties of the first plate hit for all of the plates (the only real property that is needed for the M79APCLC program is the % Elongation).

Another possible reason for the discrepancy between my formula and the US Navy formula is that the US Navy formula is based on the standard early-WWII US Navy hard-capped projectiles that had rather thick caps with cap faces of roughly a tapered flattened-cone shape, which may tear the laminated armor plates open more easily at high obliquity impact than a solid plate would be by peeling up the top layer like a wood plane, forming the spur, and then attacking the lower layer with the upper layer actually helping the penetration of the lower layer by the spur preventing the blunt cap face from moving forward and up and thus forcing it down through the thinner lower layer. They thus might have been assuming only highly-oblique hits. If this is so, then it depends a lot on the detailed design of the projectiles attacking the plates, since each nation had its own AP cap designs, which were radically different from each-other (rather amazingly so, given that they were for the exact same purpose). The French projectiles used a pointed, blunt-cone as their cap face that tapered rather a lot before forming that blunt tip. This shape would tend to glance off rather more easily than the US design or, even worse, the German caps, that were shaped much like Mexican sombreros with central domes with wide flat brims and a sharp corner at the edge that could dig into a plate deeply on initial impact. My formula is based on bare-nosed pointed projectiles, which ricochet rather more easily at high obliquity.

To see if using my M79APCLC program changed anything, instead of the DeMarre Formula for adding the KE of each plate if they were spaced, I assumed normal impact (no obliquity effects due to nose shape) and used the 14" Mark 16 AP projectile (1500 lb) and the 8" Mark 21 AP projectile (335 lb), both with their blunt AP caps attached, so M79APCLC is probably going to be off somewhat (but still closer than the DeMarre Formula would be), and I got 5.55" for the 14" projectile and 5.98" for the 8" projectile, compared to 5.96" for my DeMarre Formula approximation. It does not matter which plate is hit first in the spaced array. Note though that the 14" gives only 0.143-caliber for the 2" plate, which is a little low, so the addition formula is no longer in the middle-thickness range. Even so, the total deck thickness would be (7" + 5.55")/2 = 6.28" for the 14" and (7" + 5.98")/2 = 6.49" for the 8" projectile, both significantly larger than the US Navy approximation with the 5" plate on top (but pretty close to my estimate if the 2" plate was on top).

If the laminated plates are assisting each other compared to spaced plates of the same type and are thus giving a BETTER resistance than spaced armor, and the US Navy discussions on this topic all do state this to be true, just as my own data indicates, then it is simply not possible that the laminated armor is WEAKER than the plates spaced apart, yet the US Navy 0.7 Rule formula gives just that result applied to the 5" plate first, since the effective thickness of the 2" and 5" as spaced plates are 5.55" and 5.98" for the 14" and 8" projectiles, respectively, from M79APCLC (which is essentially the same formula that the US NPG itself developed at this time) and BOTH of these are GREATER than the 5.5" result of the 0.7 Rule with the 5" plate on top. It seems that when using the US Navy 0.7 Rule, you rearrange the laminated plates in all possible orders, apply the 0.7 Rule to the uppermost plate in each arrangement, and always use the THICKEST result with the 0.7 Rule as the one to use as the final deck thickness (using the thinnest plate to apply the rule to) -- or skip all of this and use my DeMarre Formula approximation, which doesn't care about the order, except for the % Elongation using the uppermost plate value.

II. Projectile Damage/Deflection Effects.

A. Pre-Mature Fuzing.

One of the initial uses of spaced armor was to set off the fuze of an impacting projectile so that it blows up before it can get too far into the ship's hull (this obviously was of no consequence for restricted spaces like turrets, barbettes and conning towers). These internal plates would also stop the fragments of exploding projectiles outside the armor or when they barely pierce the outer armor and explode (in WWI, coal bunkers located behind the belt armor added to this protection by smothering the blast of a projectile if it penetrated the belt armor). However, this was predicated on the projectiles not having long fuze delays or having sensitive fillers that exploded while the shell was penetrating the plate (Lyddite/Melanite/Shimose (picric acid, trinitrophenol) and black powder). During WWI, both of these were gradually eliminated in some countries (it took until 1931 for the Japanese to give up on too-sensitive Shimose in APC projectiles and until 1928 for the US Navy to finally get effective tetryl boosters to properly detonate their Explosive "D" (Dunnite, ammonium picrate) fillers and, I think, adopt delay-action fuzes in their AP projectiles, so the change to more modern fuzes and fillers took rather a long time after WWI to finally become the norm), with the British adopting a relatively reliable 0.025-second delay fuze, the Shellite insensitive filler, and, finally, APC projectiles (the 1918 Greenboy designs and their immediate successors) strong enough to remain in one piece much of the time after punching through thick armor at a moderate obliquity (up to 40 degrees against half-caliber plate, which is amazing for the time). The use of such outer thin armor to knock off the blunt AP cap also improves the deck armor resistance, since the weight drop directly decreases penetration ability and the much more pointed nose of the shell without the blunt hard AP cap has more chance of skipping off at high obliquity. This becomes one of the more important purposes of such spaced armor.

By WWII, almost all projectiles and most anti-ship bombs had short-to-long-delay fuzes (0.01-0.4 second, with most in the 0.025-0.035-second range), so the use of spaced armor for this purpose would only work under some cases where the shell is hitting from the side against the upper hull at such a shallow angle that it has to pass almost halfway through the ship before it hits the lower main armor deck, very possibly exploding first. The use of thick weather decks -- 1"-2" thick -- could stop large General Purpose bombs and perhaps slow down SAP and AP bombs dropped from a low altitude so that they might explode before crossing the distance between the weather deck and the main armor deck (though going almost straight down does not give the delay much time to work before hitting the main deck armor, which negates this fuze-delay protective effect). Thus, the use of spaced armor to set off fuzes was rather useless by WWII against most weapons. It was much more important to stop the weapon or at least reduce its penetration power so that it has less chance of penetrating the main armor (deck armor for the most part here).

One exception to this ineffectiveness of the use of the projectile's fuze delay against it is the case of the British versus BISMARCK, since the British retained their rather short circa-0.025-second late-WWI fuze delay through the end of WWII and the German ship was about the last one to use the WWI-era standard 2-deck-space "protective" deck arrangement with the main armor deck very close to the waterline and the weather deck made thick enough to guarantee the fuze of most shells would be set off if they were hitting the decks at a steep enough angle to ensure proper fuze action (under 70 degrees Impact Obliquity or over 20 degrees Angle of Fall).

Using the 1937-lb total weight and circa 1570-lb body weight 15" Mark XIIIA APC projectile from the HOOD against the BISMARCK, with a 20' two-deck spacing between the 2" Wh weather deck and the 3.15" Wh main armored deck over the amidships region near the waterline (an old WWI deck design, as in the BADEN, but somewhat thicker), we can see if there is any use to setting off the circa-0.025-second-delay base fuze in the British projectile.

We use a British Form "A" projectile with a Form Factor of 0.7235 to match known range table data in Bill Jurens's and my Exterior Ballistics 6.0G program for this analysis. Adjusting the range until the 3.15" Wh armored deck is barely penetrated, we get a Range of 20,003 yards, a Striking Velocity of 1387 ft/sec, and an Angle of Fall of 21.95 degrees (an Obliquity of 90 degrees - Angle of Fall = 68.05 degrees) on the 2" deck and a Striking Velocity of 1203 ft/sec and Impact Obliquity of 65.4 degrees on the 3.15" deck (note the small 68.05 - 65.4 = 2.65-degree Deflection Angle of the projectile as it goes through the relatively thin 2" plate). Even though the projectile barely penetrates, most of this is due to glancing effects, not stopping the projectile, so the projectile penetrates the lower armor deck with a Remaining Velocity of 565 ft/sec with and Exit Angle (from the vertical) of 53.8 degrees. However, the 0.025-second-delay base fuze would usually be set off at this Impact Obliquity on the 2" deck (a 0.5" deck would do it at this Obliquity), so the projectile would probably explode between the decks -- it had to move 53.5' at a slant and would only go (1203)(0.025) = 30.1' before exploding on the average -- before hitting the lower deck, reducing the impact mass on the lower deck to only about 33% of the projectile's body weight, making penetration impossible.

To be able to penetrate the lower deck, the projectile would need to be falling at a high-enough Angle of Fall to make the slant distance times the 0.025-second delay at the Remaining Velocity after penetrating the 2" deck = (the slant distance between the decks) + (the length of the projectile body, since the AP cap and windscreen are now gone) + (some added effective length due to the slowing of the projectile as it passes through the 3.15" armored deck to get all the way through that lower deck before exploding). Only then would the projectile have a better than 50-50 chance of penetrating and exploding under the lower armor deck. This would increase the minimum range to penetrate the BISMARCK deck armor significantly. Thus, in this case the use of early fuze activation does work.

Using a body length of 3 calibers and adding another 2 calibers to make sure that the projectile gets entirely through before exploding, we get a required distance of

$$[20'/\text{Cos(Exit Angle)}] + (5)[15''/(12''/\text{ft})] = (0.025)(\text{Remaining Velocity})$$
$$\{[20'/\text{Cos(Exit Angle)}] + 6.25'\}/(\text{Remaining Velocity}) = 0.025$$

where the Exit Angle and Remaining Velocity are after penetrating the 2" weather deck. Using the EB 6.0G and M79APCLC again and walking through ranges, the above formula is satisfied when the Range is about 31,700 yards (1318 ft/sec and 41.5-degree Angle of Fall) with a gun Elevation of 34.5 degrees.

Since the HOOD can't elevate its guns that high (30 degrees maximum, if I recall correctly), the BISMARCK's use of the 2-deck space between the weather and main armored decks works against the HOOD at all ranges (any British Naval APC projectile, in fact, except for the NELSON and RODNEY at near maximum range -- they could elevate their guns to 40 degrees) when it is hitting the BISMARCK's decks. Note that this is ONLY because of the large 2-deck space between the two armored decks and the rather short fuze delay used. Most non-British AP ammunition made after WWI had much longer fuze delays in their AP ammunition: 0.033-second for the US Navy in WWII, 0.035-second for the German Navy, 0.4-second for the Japanese Navy (for a long underwater distance if the shell hits short of the target), and so forth, so the fuze delay effect would be much less useful against such ammunition even with a BISMARCK-type deck arrangement. Also, most post-WWI warships had only one deck distance between the lightly-armored weather deck that can initiate the fuze, if the ship even had such an armored weather deck (not used in a number of ships) and the ship's main armored deck, so the numbers needed to reach the lower deck from the weather deck are halved, or eliminated altogether if there is no armored weather deck, which means that there is only a rather small added range, if any, between the range that can punch through both decks in most of these newer ships and the range that the fuze delay allows it to do so.

Note that if the German WWII APC base fuze 0.035-second delay was used, the shells could go about 42' on the average and, with the statistical variation between fuze delays,

a significant chance (perhaps 10%) of the shell reaching across the 53.5' slant distance to the armored deck at the 20,003 yard range. Note that this greatly compromises the invulnerability of the German ship's deck arrangement. This is virtually identical if the US 0.033-second average delay was used. If the Japanese 0.4-second delay is used, no between-deck distance has any meaning whatsoever as to the effect on the fuze.
This aspect is not a major consideration in most ship-versus-ship actions in WWII, though obviously British-versus-German battles are the exception.

When the decks are all laminated to a single multi-layered plate, this use of the fuze delay disappears, so spaced armor does have some useful benefits under some conditions, even if not quite as strong as the laminated or single solid plate cases.

B. Projectile Deflection.

One thing that most designers of spaced armor seem to ignore is that a projectile or bomb hitting a plate at an oblique angle is not only deflected when it ricochets off, BUT ALSO WHEN IT PENETRATES, but in this case the other way, so that it comes out the plate back in many cases closer to normal to the plate back surface than its original impact obliquity. That is, a Deflection Angle = (Obliquity Angle - Exit Angle) exists. The higher the velocity above the minimum bare penetration velocity, the less deflection occurs, but you have to hit at a VERY high velocity percentage over the bare minimum complete penetration velocity -- US "Navy Ballistic Limit" (NBL) -- to reduce this deflection to a negligible amount (make the Exit Angle the same as Impact Obliquity Angle). In almost every protection diagram I have ever seen from any Navy (Austro-Hungarian, German, French, and British), the path of the projectiles is shown going in a straight line though all of the plates, which is rarely ever true, as diagrams of the trajectories of actual projectile impacts (such as those on British ships at the Battle of Jutland from German shells and impacts on captured German ships by British guns after WWI) show conclusively.

Note that in the HOOD versus BISMARCK discussion, above, when hitting thin plates at well above their bare minimum complete penetration velocity, the Deflection Angle is indeed rather small and ignoring it does not change the results of an analysis much (there are much biggest "guesstimates" involved than that one). This is definitely NOT true when the first plate or plates hit are of substantial thickness and the Obliquity Angle is significant, however.

The deflection when the shell ricochets from an armor plate (or from anything else it hits along its path through the ship) can cause it to tear up quite a bit of real estate in the ship's hull as it bounces around. While probably not as damaging as punching through the main armor, this sometimes quite long trip through the ship (especially if the projectile's fuze has been damage by the initial ricochet from a heavy armor plate at a high obliquity angle -- the base slams down on the plate as the nose ricochets away, causing damage in many cases) can cause all sorts of debilitating damage after the battle. For example, one of the reasons that GRAF SPEE had to go into Montevideo rather than trying to escape back to Germany after its battle with the three British cruisers was damage to things like its galley and so forth that would have made such a rather long trip difficult, if not impossible. Not everything important can be protected by armor, with usually only the things of immediate importance to the current battle being protected adequately, if that (the HOOD is an example where even the important parts of the ship, the main magazines here, were not adequately protected under the conditions of the battle when it was blown up).

Deflection after penetrating an armor plate is another matter. The plate both slows the projectile down by stealing energy when torn open and exerts asymmetric forces on the projectile at oblique angles to rotate the projectile nose both initially away and, finally when the nose digs in deep enough, into the armor plate to penetrate it. This deflection when parallel spaced plates are used causes the next plate in line to be hit at a steeper angle (closer to right angles) and this makes that plate weaker than it would otherwise be, in many cases changing a non-penetrating hit to a penetrating hit. In fact, US Army trials, where this is a much more critical problem -- deflection into weak spots, called "shot traps" -- such instances of deflection changing the results are much more common in armored vehicles since they hare hit so much more than ships are in battles (there are more of them and more battles!) and the chance of such a weak spot hit is thus more likely if it is not prevented by optimized design to prevent such things. Anything can be a shot trap if it prevents the projectile from going anywhere but through the plate, making even the most impervious vehicle a wreck -- there is one case where a hard-point lug for lifting a thick plate in the front of a tank was hit right where it and the plate merged by a projectile that was normally totally incapable of penetrating that thick plate, forming a wedge-shaped pit where the projectile could not ricochet and thus punched right through and knocked the tank out. Deflection when you don't want it and no deflection when you do are thus both problems that are to be avoided whenever possible.

Interestingly enough, if you take deflection into account, you may find that you can have TOO MUCH ARMOR (!!), since the plate is thick enough to deflect the projectile into a place you do not want it, but not thick enough to slow the projectile down enough to prevent it from causing heavy damage to that place. There was a definite need to have the weather deck armored enough to make sure that large General Purpose (GP) bombs explode on the weather deck (1" armor steel is barely adequate, with 1.5" being satisfactory, and 2" being somewhat "overkill" in this regard) and, though making a big mess of the outer hull, superstructure, and area above the main armor deck, fail to penetrate into the upper hull to detonate directly on the main armor deck itself. The armored deck is in most ships a major structural component of the hull girder and a large hole or even a big dent can compromise the ship's hull strength. Also, while capable of resisting the direct penetration attempts of AP projectiles at high obliquity or AP or SAP bombs at a steeper angle but lower striking velocity, it is not capable of resisting the shock effects of large GP bombs (1000-2000 lb) detonating directly on its upper surface. If they did, they could cause considerable shock effects throughout the ship (they have much more energy in concentrated from than the mere velocity-related energy of an impacting AP projectile or bomb), resulting in power failures; broken vital equipment used for fire control, propulsion, and ventilation; and even leakage through cracks in the hull. Damage to the weather deck and upper hull and superstructure is much less critical to the survival of the ship under attack.

However, the weight devoted to the weather deck armor has to be gotten from somewhere and this is usually in the weight (thickness) of the main armor deck.
We will ignore the pre-mature fuze delay effect here, since it doesn't work for some long-delay shells even if functioning properly and has no effect if the fuze is a dud, which happens rather often in APC projectiles -- several German shells in the BISMARCK battles, both from BISMARCK and from PRINZ EUGEN, did not explode, for example. Neither did some used by the US against the French at Casablanca. Thus, a solid shot projectile might pass into the target through its armor and cause all sorts of damage bouncing around -- sometimes just as much, if not more, than it would have done if it had exploded properly! This is especially true if the projectile breaks apart during the penetration process, since then it acts much like it had exploded, though with much less incendiary effect, of course.

Using the HOOD example, we have 20,003 yards for the ability to punch through the BISMARCK's pair of armor decks, 2" over 3.15" amidships. If the plates were 1" over 4.15", this changes to 23,330 yards, though at the risk of not always setting off all GP bombs hitting the weather deck. (You can't really eliminate a heavily-constructed weather deck, since it has to stand up to severe weather, if nothing else, so you might as well use armor-class steel and thicken it slightly, at least, if you are worrying about aircraft bombs, so I am not including this option.) If you change this to 1.5" over 3.65", you get 21,810 yards. However, if you go the other way and make the two decks 2.5" over 2.65", this changes to 18,020 yards. In this last case the deflection by the 2.5" upper deck was about 3.6 degrees, the worst case; without this deflection the minimum range would be closer to 19,000 yards, so it is small, but not insignificant.

If we reverse the thicknesses to 3.65" on the weather deck and 1.5" on the main armor deck, the penetration range for the array becomes 19,795 yards. This is interesting for several reasons. First, the main belt would have to be raised and/or upper the side belt would have to be thickened to reduce the striking velocity on this thin lower deck from the side, which adds a lot of extra weight, so from that angle, this is a poor design choice. The thick weather deck would cause a major weight unbalance to the ship, reducing stability appreciably, which again is a bad idea. Third, THE 1.5" LOWER DECK HAS NO EFFECT WHATSOEVER ON THE DECK ARMOR RESISTANCE!!! That is, when the 3.65" upper deck is penetrated, even exactly at its ballistic limit at 19,795 yards (1392 ft/sec at almost exactly 68 degrees Angle of Fall), the Remaining Velocity of about 770 ft/sec and the Exit Angle (= Impact Obliquity on the 1.5" lower plate) of 58.5 degrees makes the Remaining Velocity almost DOUBLE what the 1.5" Navy Ballistic Limit gives against the 15" projectile at this Impact Obliquity, even with its body-only weight of about 1570 lb!! This is due to the glancing contribution of the resistance of the 3.65" upper plate at this high obliquity never stopping the projectile, but just slowing it down, whether it penetrates or not. In this case, this slow-down is never enough to be below the 1.5" NBL if the projectile penetrates the upper plate. The lower plate would have to be about 50% thicker or more to contribute anything at all to this scenario, which greatly increases the weight of the deck array to no purpose whatsoever.

This is a very good example of how projectile deflection completely changes the results and can really ruin the design if not taken into account. The upper plate here is so thick that it completely negates any positive effects of having a thin lower plate at all (other than as a splinter screen to catch fragments if the upper plate has a hole blown in it by a large GP bomb -- it would take a pretty big bomb, though). A real "Catch 22" situation! You obviously CAN make a plate too thick for optimum resistance!! The original BISMARCK 2" over 3.15" array was getting pretty close to this cliff for some projectiles -- medium-to-large-size shells hitting at a rather low striking velocity, such as with a reduced charge, which would have a larger Deflection Angle on penetrating the upper plate at any given Impact Obliquity -- indicating that the 2" upper deck was not optimum. The 1.5" over 3.65" distribution seems to be the better design for this reason and because it gives you about 2,000 yards -- 10% -- more to the minimum deck penetration range, as noted above, than the actual design.

Again, if the plates were all laminated into one solid plate or a single plate of the same total weight was used in their place, all of this would go away as far a pure penetration resistance is concerned, with no real compensation for using a spaced array at all in this case. Spaced armor is always a poor choice when taking this situation into account.

C. Projectile Damage.

This is similar to using the projectile's fuze to reduce the ability to penetrate the later plates in a spaced array, but in this case by directly damaging the projectile in some significant manner by the plate itself, whether or not the shell has an explosive filler. If the projectile can be broken into pieces, be bent or compressed significantly, or be caused to yaw (swing its nose out of alignment with its forward motion so that it hits the next plate at a cocked-off angle) or tumble by the first plate hit, it usually will have a much worse time trying to penetrate the later plate(s). Break-up is the best bet, since it spreads the pieces over a large area on the next plate, as well as possibly causing some of the pieces not to penetrate the first plate and reducing the projectile's total impact energy against the later plates. Under the best conditions, spaced arrays that can break up the impacting projectile on the first plate can stop amazingly powerful attacks -- this is used quite successfully in the International Space Station to protect against micro-meteorites that would otherwise gradually make the living spaces into sieves.

Unfortunately, with thin plates in such a spaced array, they have rather little ability to damage a well-designed AP or even SAP/base-fuzed Common projectile (other than removing the windscreen, hood, or AP cap of the projectile, if any) , even at high obliquity. Thus, penetration-reducing damage is usually not an option. Damage due to base slap as the shell slams its lower body against the plate at high obliquity when it ricochets or penetrates can sometimes render the shell "ineffective" with a blind fuze or less-than-optimum explosion even if the fuze works, but this works against the use of the fuze delay to prevent penetration of a spaced array, assuming that is a viable option, too.

Causing the shell to yaw or tumble is much more frequently a side-effect of highly-oblique impact, penetrating or not. When it happens, this usually will significantly reduce the penetration ability of the shell as it tries to force its way through the later plate(s) tilted or even sideways. However, as with the Deflection Angle effect, sometimes the yaw can make a highly-oblique impacting nose hit at an angle that helps it to penetrate by reducing the glancing effects, so this is not always a benefit. This kind of thing is statistical, with mostly a benefit, but not always. With very large shells hitting thin plate, the amount of yaw achieved is usually rather small, though, even under the most optimum conditions, minimizing this as a viable way to prevent penetration more often than not. The greater the Deflection Angle, the more yaw will occur as the spinning shell over-compensates as it tries to get back going nose-first, swinging the nose into a conical spiral as the projectile moves forward ("nutation") -- this also happens with long, fin-stabilized projectiles, but not as easily (this does not concern us here, of course).

The stripping off of the usually-very-blunt AP cap from the shell by the first plate (if thick enough) is a good thing in that it decreases the weight of the projectile significantly, usually 10-20% including the windscreen, too, and makes the nose more streamlined and less able to prevent being caused to glance off at high obliquity. The projectile nose under the cap was usually optimized for penetrating thick homogeneous armor at medium obliquities in WWII (in WWI the long points on most projectile noses were for right-angles penetration only) and had a blunt point -- the US and Japanese had the bluntest points at the beginning of WWII to improve penetration against deck armor with or without the AP cap at long range oblique impact (both assumed long-range fights in the Pacific early in any war, which did not happen, with a couple of exceptions, in WWII due to the introduction of aircraft into the war), with the US going even farther against deck armor early in WWII with oval nose shapes with no point whatsoever (this cost a small amount at right angles against thick homogeneous armor (rarely used by anyone but the US, however), but helped by improving penetration up to 25% against thinner deck armor in the long-battle-range, 50-60-degree-Impact-Obliquity-angle range!!). The blunt AP cap helped all projectiles (though the US and Japanese shells did not really get much of a nose-shape benefit since they had a blunt nose, cap or not), so stripping it off had some effect in increasing the minimum range that a given deck could be penetrated -- it depended on the deck plate thickness hit, since breaking or shattering the AP cap on impact with thicker plates could reduce its benefits even against the plate removing it. Stripping off the cap by a thin over-plate thus was of some benefit to the protection of the ship from plunging shellfire by making the later plates -- and even the initial plate if it could shatter or break up the cap -- more resistant. It was not a really major consideration, though, compared to other methods of trying to impede an attacking projectile.

If the second plate in a spaced array is face hardened, a thin first plate, by removing the projectile's AP cap, can also cause the projectile to shatter on the second plate, degrading its ability to penetrate the second plate at low obliquity. Thus, the thin first plate is causing projectile damage, but indirectly. However, note that as obliquity goes up, this shatter also impedes the ability of the second plate to cause glancing (the nose cannot be pushed away when it is in small pieces!) so if the second plate is hit at a highly oblique angle, the shatter may actually allow the projectile to penetrate MORE EASILY -- though in pieces, to be sure. This high-obliquity resistance degradation effect due to shatter has made a number of spaced armor experimental designs that attempted to use decapping for this purpose fail, since, in addition to the added weight of the supports for the first thin plate, the second plate might be hit at a more extreme obliquity sometimes and the design in those cases actually be worse than not having that thin plate at all!

By laminating the armor or using one solid plate, the projectile damage from the impacted plate could go up significantly, but the use of breakage to reduce penetration against later plates by spreading out the projectile pieces is totally lost. The benefit of such thicker single plates would mostly be to increase damage due to base slap at high obliquity that can reduce or eliminate the explosive effects of the projectile after penetrating the armor. While possibly important in some cases, a large solid shot passing into the crowded space behind the armor hull amidships (through a boiler or engine or, worst case, magazine) can have very bad effects even if it doesn't explode, so this benefit is important, but not as important as some other considerations in armor design.
For less important areas of the ship, it might be better to have the plates so thin that they do not set off the projectile's base fuze (which needs a solid impact shock to work), thus getting the benefits of the projectile damage to the filler/fuze without the weight penalty. The shell would merely punch a single set of in-line holes as it passed through that part of the ship with hopefully minimum damage. This is called the "all-or-nothing" armor arrangement and was tried in US WWI-era battleships. Unfortunately, as AA guns, radars, and so forth became more and more important, using light protection against nearby fragmentation effects from exploding bombs, torpedoes, and shells (hitting the ship itself or near misses) -- eventually including Japanese kamikaze aircraft in US warships -- became mandatory and the all-or-nothing rule had to be compromised, though obviously some parts of ships were much more heavily protected than other parts, even here.

III. Structural Considerations.

While an important part of a battleship, armor is not the most important part of the design. The ship has to float with some minimum stability when rolling, move about under its own power in some sort of efficient way, use its weapons efficiently when fighting (its purpose in the first place), and resist damage due to underwater hits, storms, running aground, etc. either during or, more usually, between battles (most warships don't "war" very often in their lives, BISMARCK being an exception in its very short career). Thus, the structure of the hull and the armor have to "get along" to have a well-balanced design.

One important consideration is that there be no single-point or single-line failure that can cause major ship damage. The German Navy in WWII did not follow that rule and had several ships have major damage due to a single weld failing, because that weld happened to be carried over a large length – one German cruiser had its entire stern almost fall off from a torpedo hit when such a single load-bearing transverse weld failed entirely across the stern.

US designs had this eliminated as much as possible by not having welds or riveted areas that went very far before they were interrupted by something. For example, construction plate edges were stepped so that the welds were staircase-shaped zig-zags, rather than a single vertical or horizontal line across the entire plate edge. Another thing like that was making sure that plate edges and the ends of back support beams and columns did not line up -- the attachments between the supports pressed up against the middle of a plate, not an edge between two or more plates. Shock effects and direct force applications did not have a direct path through any structure and random breakage would very rarely line up to cause a widespread failure.

One other method of doing this is to use laminated plates, where the two or more separate plate layers also do not have their locked-together edges lined up. This actually makes such laminated arrays stronger than solid plates against structural failure, though it can reduced the direct ballistic resistance compared to a solid armor plate. For example, at Pearl Harbor, two old WWI-era US battleship turrets had their 5"-thick solid roof armor penetrated by Japanese AP bombs (remanufactured ex-16.1" APC projectiles), not by punching through the plates themselves, which turned out to be impossible, but because the bombs hit the turret roof armor from the rear at about a 60-degree angle of fall just behind where two roof plates overlapped (the rear plate edge was tucked under the front plate edge to increase resistance to gun projectiles hitting from the front of the turret, where the expected enemy warship would usually be). Because the plates were reinforced from the frontal direction, they purposely allowed the plates to be weak if hit from the rear, so the bombs tore the rear plate's front edge bolts and rivets holding it to the rear edge of the of the forward plate, bending down the rear plate and opening up a mouth-shaped opening between the upper side of the rear plate and the lower side of the forward plate, and allowing the bombs to squeeze through the narrow gaps, which severely damaged the bombs, but allowed them to put the turrets out of action until extensive repairs were made (I do not think they were manned at the time, luckily). This was due to the roof plates extending entirely across the turret roof in one piece and thus their straight-line joints having a considerable unimpeded length that could be bent down. If the plates had been attached to each other in a zig-zag manner from side to side or had been made of two 2.5" layers with offset edges in each layer, any roof openings formed would be much more difficult to create and, even if formed, probably would have been smaller and the damage inside the turrets much less extensive. I believe that strengthening the turret roofs of the damaged battleships at Pearl Harbor was one of the general upgrades to most, if not all, of these older ships. (US WWII battleship turret roofs were also solid plates, but were not overlapped like that, with the plate edges solidly keyed together, double-bolted to the underlying support structures along their edges, and reinforced from below at their edges and across their centers equally in all directions, so bomb or projectile hits from any direction would be resisted equally if they hit next to or on a joint between two plates. Pulling the roof plates apart at their joints to get a "poor man's" penetration would be much more difficult than with the WWI battleships.)

Spaced armor also allows increased strength if the plates can be worked into the structure without compromising the plate's resistance or the structure's ability to deform slightly as the ship is put under various forces, say during a storm. This makes damage to any spot on the top, bottom, or sides of this box of much less effect, since there is still the strength of the other side of the box to keep it undeformed. Note that usually face-hardened armor is too rigid to be used like that, cracking if not isolated from the twisting, bending hull, but it turns out that circular face-hardened armored barbettes can be self-supporting due to their inherent rigid reinforcement between plates, as long as the under-layer of heavy supports deep in the ship holding the bottom edge of this armor is tough enough to handle the hull stresses and still isolate the rigid barbette armor from any distortion of the ship the barbette is attached to. Note that use of heavy armor in a structure can also force the designer to add greater structural support to handle the added weight and, if not done carefully, can make the final result heavier than a simpler design with equal usefulness. The designer has to juggle a lot of "balls" at the same time to come up with a good, if not always optimum, design that satisfies all requirements.

US WWII battleship turrets and barbette structures were much simpler, lighter in weight, and yet stronger by intelligently using the barbette armor itself to hold the internal structures that attached the rotating turret to the barbette upper edge -- but which only held the turret from side-to-side motion, not directly supported its weight, which was transported down the center of the barbette as a rotating inner structure pressing down on the lower hull girders.

Thus, sometimes using spaced and/or laminated armor, or even at times solid armor plate, gives all-round better efficiency in reducing ship damage from hits or lightening the ship by incorporating the armor into the ship's strength structure even if it costs a small amount of ballistic protection to achieve this -- stopping a projectile that then splits a major seam open and floods a large part of the ship does not seem to me to be a good compromise in the use of that armor, if some of the plating could have been used to also reinforce that seam structurally, even if it caused some acceptable loss of maximum possible ballistic protection against direct hits.

Note that when using spaced or laminated armor, the support and attachment structures can be more complex than simple single plates. This added complexity and weight has to be carefully weighed (literally!) against any benefits of using a given design. Sometimes a good idea turns out to be impractical in its actual implementation due to this. As is said, "The Devil is in the details!"

--The End--