COMPARATIVE ANALYSIS OF STEEL AND CONCRETE

IN STRUCTURES

THESIS FOR DEGREE OF B. S.

IN CIVIL ENGINEERING

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BY

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THESIS

In order to visualize more clearly the merits of both steel and concrete structural designs an attempt will be made to compare these materials in the ways in which they control the factors that lead to their selection. Many of the features that are characteristically allied to steel permit its use in fields not invaded by concrete. To such uses of steel no further mention will be made. Only to the uses of steel in places where some considerable difficulty obtains in attempting to choose which materials are the best to use. will this treatise be devoted.

Good engineering calls for the use of those materials which, under given conditions, will most efficiently and economically meet the required conditions. There is no particular material nor any one type of construction that proves to be the best universally. The proper combination of materials structureally and otherwise requires diligent and well directed study.

The features to be investigated in this thesis are time required for construction, labor problems, effect of weather, maintenance, and cost of construction.

A considerable space will be allowed for the relating of the practice of the Michigan State Highway Department in its construction of highway bridges. The results of experience of contractors, and the history of bridge development in Michigan will be briefly sighted as it affects the topic.

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Each bridge that is designed presents problems that are characteristically its own. These problems may be a combination of fundamental or secondary factors of such an order that another bridge like it might not be required for quite a number of years. This fact alone points to the great number of designs the department is required to have on hand. Until only [illegible] the bridge department had put in [illegible] bridges of which [illegible] or [illegible] were concrete girders. Up to Feb. [illegible] were skew bridges. Of the [illegible] bridges [illegible] would be square span. Of these [illegible] there [illegible] - [illegible]' girders with [illegible]' roadway, [illegible]' abutments, [illegible] deg. crossing. Plans might be used only three to six times in [illegible] cases. This is only considering degree of crossing, length, abutment height, and roadway. Other factors would make the probability of duplication of plans even less.

An outline of the factors of design in use by the state bridge department is as follows:

Fundamental factors of design:- 1. Clear span. 2. Clear roadway at hubs and curbs. 3. Height from crown of roadway to bottom of footings. 4. Angle of crossing.

Secondary factors of design:- 1. Necessary roadway from crown of roadway to bridge seat. 2. Provisions for maintaining traffic. 3. Lighting requirements. 4. Aesthetic treatment required. 5. Street, property, and protection arrangements. 6. Limitations in elevations due to high and normal water level, logging, ice conditions, and roadway grade. 7. Necessity of building bridge on a grade. 8. Provisions for a public utility, unusual loading, increase in width for sidewalks, etc. 9. Accessibility of materials and transportation changes, and conditions. 10. Height from crown of roadway to natural elevation of banks. 11. Adequacy of width of present structure. 12. Character of foundations. 13. Wing treatment for protection and economy.

It is evident that it would be economical to standardize superstructures since, of variables of width and roadway there are but few widths used and sidewalks are comparatively few. Nevertheless it is not the rule that plans can be duplicated. That bridge which is most easily designed would then be the best if other conditions were the same.

Aesthetically the public eye demands an arch. An arch is peculiarly unsusceptible of standardization. It requires a hard pan or rock bottom and a full knowledge of this beforehand. Also a full knowledge of the lay of the ledge is required. The span is inseparably linked with the height and thus decreases to a small percentage the probability of the reuse of the span. The type of abutment is inseparably linked with the height and span and rise. In addition to the lack of economy of standardization the time necessary for arch analysis and detail is about twice or three times that for any other special plan. The probability of widening such a span economically is far less than with almost any other type of bridge design. In addition the greater portion of the bridges in Michigan require piling, and further require more waterway than can be secured for equal spans of arches as compared with trusses and girders, and, further, Michigan valleys are too low and flat to furnish sufficient rise for for arch spans without resorting to very flat rise ratios. It would seem then that the arch should be considered only for special uses where it may prove desirable and appropriate. Prior to July 1920 1[illegible] of the 240 bridges are shown as arches. Many were built on piles on extremely poor bottom and but few of them on foundations which come under the hardpan or rock classification.

This evidence seems sufficient to eliminate the arch as a standard superstructure.

Consideration of steel superstructure such as girders and trusses of the through type will next be given. First the objections to steel superstructures for highway bridges as given by the state bridge department will be listed.

1. Superior beauty of steel to steel superstructures.

2. A steel superstructure must be artificially protected against the weather and this protection is short lived, not ordinarily over five years, and at the best, the parts which need protection are generally inaccessible for painting.

3. To properly protect such a structure costs about three per cent of its orginal cost each year. This figure does not include any depreciation or sinking fund allowance.

4. Up to 100' spans, as will be shown later on, steel superstructures with concrete floors have a greater first cost than concrete girders designed for the same capacities.

5. Neglect of maintenance is a serious and dangerous thing and while the present organization may be efficient in its line, there is no guarantee on the future; and in addition, maintenance organizations are not always of the high class that are best suitable for such work. Maintenance neglect is, then, a serious reflection on the policy of using steel superstructures.

7. There is usually no meaner job to inspect for maintenance than a steel structure. Water and wind carry the elements to the most remote places, and the earthly elements hold the moisture in contact with the air and steel for almost permanent periods of time. Concrete itself adjacent to steel is peculiarly an unfavorable element in the life of the steel if the air should have access to the common line of contact and particularly so if there is lime present in the concrete. Furthermore it becomes frequently impossible to clean the surfaces in contact and at which the corrosion is most severe. The inconvenience of inspection becomes, then, a serious criticism of such a design.

7. Paint crews don't clean properly, they paint over damp, dirty, and greasy places. This makes inspection more difficult. This also lends a false feeling of safety to the structures. Shortly the paint peels off. Thus the practical inability to maintain the structure is also a serious objection.

8. Expansion details on steel bridges are difficult to provide satisfactorily inasmuch as expansion planes at two levels must usually be provided for at one end of the structure. The department has recently worked out a detail free of expansion defects.

9. But few fabricating companies turn out bridge work in accord with specification requirements. The greatest criticisms apply to field connections, alignments, and fits. Concrete has the advantage over steel in that its workmanship is uniform. For steel the work is no better than the field connections however well the shop work has been performed.

10. It is almost impossible to get a good job of errection regardless of the excellence of the shop work. Very few fabricating companies of good reputation do their own errecting. They are careless in subletting the work. It takes a good sized job in a good location to tempt the best fabricating companies to do the job of errecting.

11. Whenever a steel job is let, no assurance can be given that the substructure will be ready in time

In order to make the comparison of steel and reinforced concrete more complete a specific example taken from the records will be given. The chosen bridge was originally designed for steel superstructure but later it was changed to reinforced concrete. It is located near Rockford, Mich. It embraces a span of 100' and is the first 100' concrete girder bridge to be built in Michigan. Costs are given for the 100' concrete girder with a [illegible]' roadway [illegible] while the cost for steel superstructure is based on a 16' roadway and concrete [illegible].

As stated above the bridge was [illegible] steel superstructure design and later [illegible] changed for a concrete superstructure. The abutments [illegible] of [illegible] concrete. After it was decided to build the superstructure of concrete the amount of concrete [illegible] actually [illegible] the abutments [illegible] which were to be used for the steel superstructure were eliminated. This saving in concrete could have been materially increased had the abutments been designed for concrete superstructure in the first instance. The bridge seat was put at a lower elevation for the concrete design. The seat, as designed for steel superstructure, was [illegible]' below the roadway, while for the concrete it was placed [illegible]' [illegible] of abutment [illegible]' a considerable saving in concrete was effected.

A further saving is also due to the fact that the bridge seat elevation is down 5' for the concrete superstructure, the abutment thickness being 2' while for the bridge seat elevationin the case of steel superstructure which is 5' a thickness of 5' is required. At the top of the footing the concrete abutment thickness would be less for concrete superstructure than for steel. This is due to the fact that the pressure of the backfill to be resisted by the abutment is less in the case of concrete superstructures, since all backfill pressures are above the bridge seat. That is, for the upper 9' of fill are carried directly through the concrete superstructure, whereas for the steel the abutments themselves must resist pressure from this 9' fill.

From the above facts we see that in the substructure a considerable saving was effected when the design for steel was superseeded by that of the reinforced concrete. A comparative estimate of costs with steel truss superstructure and with reinforced concrete girder has been prepared and may be found on the following page. It will be noted that the superstructure of concrete is slightly more expensive than steel, however several facts have not been taken into consideration and will be discussed at this time.

One of the important factors the bridge engineer takes into consideration is the matter of rigidity. Some of the older types of steel bridges are very poor examples of rigid structures. With the concrete superstructure as designed in this case, special emphrasis was laid in the design with regard to this factor. In a rigid structure with large inertia the tendency is for the structure to absorb the impact and live loads with but small overstresses in the members.

Comparative estimates of costs with reinforced concrete girder superstructure and with steel truss superstructure-- 1[illegible]' span. [illegible]' roadway.

Concrete superstructure and concrete abutments.

Abutments:	Lump sum	$5674.11
241 cu. yds. Grade C concrete.		
Filling		2596.00
Superstructure.		
370 cu. yds. grade A @ $30.00	$11100.00	
39350# re-bars @ .08	3148.00	
3[illegible]# Stru. steel @ .16	4848.00	
		19105.00
Cement finished abutments		[illegible].15
Superstructure		1[illegible].70
Engineering and supervision		2[illegible].72
Total estimate of first cost		$31[illegible].80
Annual maintenance.		
Annual depreciation.		
1% x 31[illegible].00--31[illegible]		
Capitalized at [illegible]%		$2619.36
Estimated total cost in perpetuity		$3[illegible]7.36

Steel superstructure and concrete abutments.

Abutments	$5740.30
Piling	2296.00
Steel superstructure	
168,000# @ .085	14280.00
Concrete floor	
43.5 cu. yds. @ $45.00	1957.50
abutments	365.13
Floor	101.00
11650# re-bars @ .07	815.50
Engineering and supervision	2310.00
Field painting	$325.00
Total estimate of first cost-----	$28276.00
Annual maintenance	110.00
Annual depr.---2% x 28277.00	565.54
Capitalized at 4%	675.54
Estimated total cost in perpetuity	$45165.48

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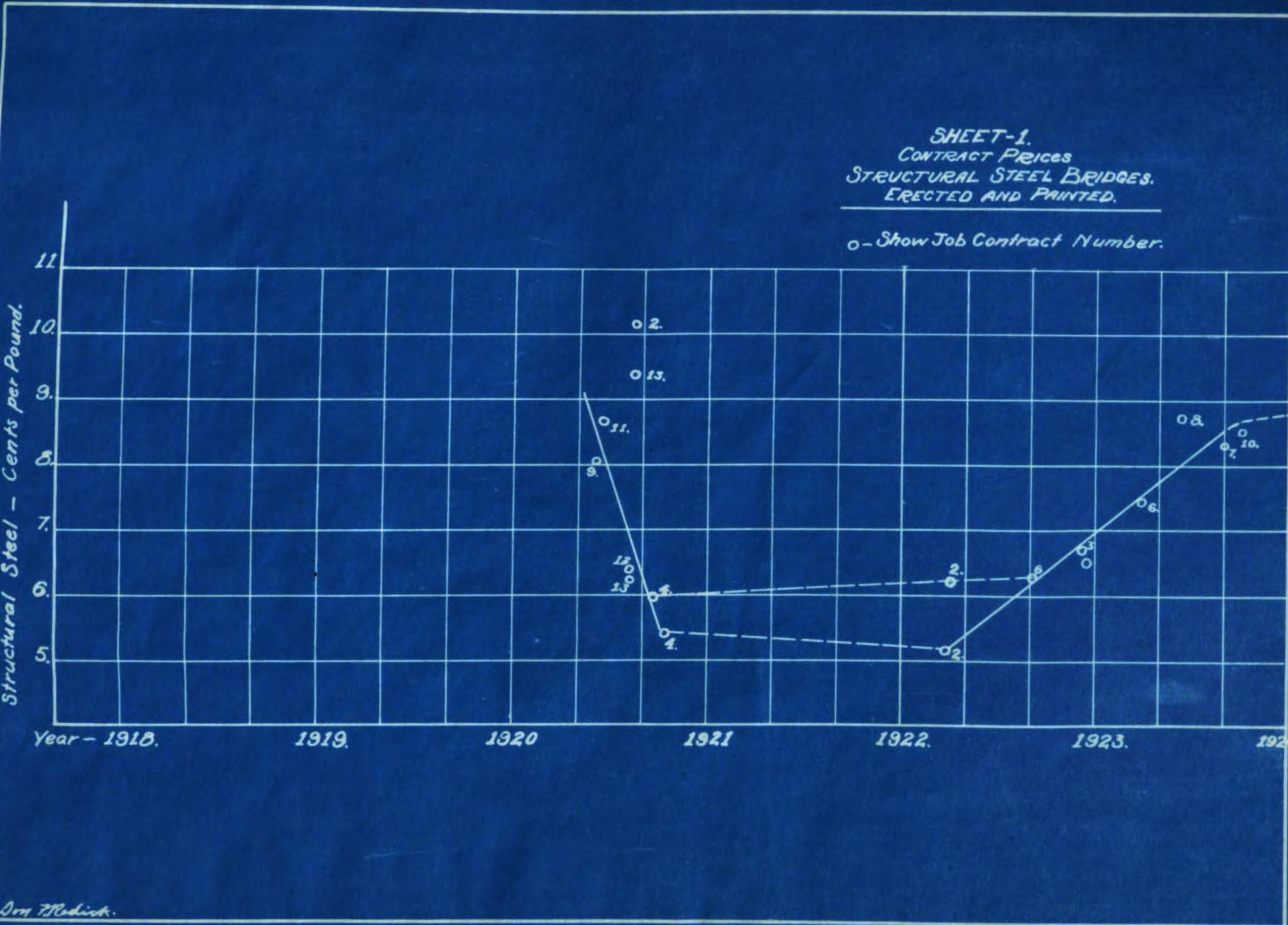
A still further saving could have been effected by having a single contractor. In the above job if the steel superstructure had been used it would have necessitated letting at least two contracts and perhaps more. Such work as substructure of reinforced concrete would be let to a separate concern while that for fabrication and errection of steel to another one or two contractors. This could be accomplished very nicely by letting the contract in one and obtain lower unit prices.

The price quoted for the steel superstructure is typical of trusses errected without field paint and this of course must be taken care of as an extra contract. The engineering supervision for the steel structure is slightly higher than for the concrete structure. In the construction of the steel structure three contracts are required - abutments - superstructure- floor. Each requires a different inspection. In addition to this a shop inspection is required on all structural steel. It will be noted that the first cost is in favor of the steel structure. Several other items, however, must be taken into account. First, the depreciation allowance on concrete is 1% annually as compared with 2% for the steel. The concrete structure will require no maintenance expenditure while structural steel will require an annual average maintenance of $110. These sums capitalized at 4% the resulting total costs are considerably in favor of the concrete.

Inaddition to this comparative data two sets of curves are being submitted. Sheet 1. shows the actual cost of the structural steel for spans ranging from 70' to 175' inclusive for a total of thirteen jobs. This curve of unit cost represents the price for steel errected and painted, exclusive of concrete floors. Sheet 2 illustrates ths price per cubic yard for concrete superstructures in place, the data being plotted for 15 different jobs, Sheet 3 represents the quantities of materials required for concrete girder superstructures in spans from 35' to 90' inclusive. Also the quantities of structural steel inthe truss structures from 75' to 175' inclusive are shown. The number of cubic yards of concrete in the concrete floors is likewise included. This sheet 3 in giving quantities has been platted in such a way that it may be used for illustrating any particular problem that might be selected. This has been arrived at by dividing the total yardage of concrete in the concrete girders by the number of square feet of the resulting roadway; also the concrete floor yardages are in cubic yards per square foot of roadway. The individual circles platted for steel giving the bridge numbers from which actual widths were taken. The concrete girder curve is platted from actual drafting room records.

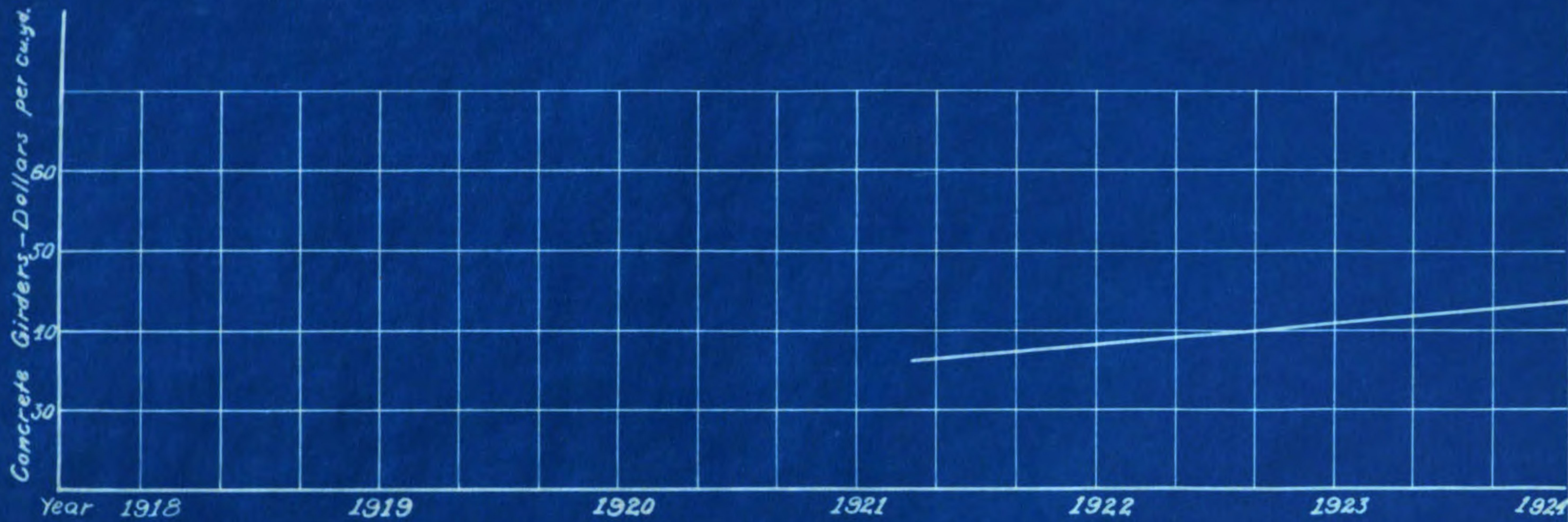
Sheet 2 is platted for maximum concrete girder span of 90'. There is a very material saving or reduction in unit costs in shorter spans and in order to prove the point, the maximum span is used. There can be no question of the fact that if economy can be shown on a 90' span with concrete a far greater economy exists for shorter spans. Sheet 2 shows that for all jobs on which a lump sum is bid the average price per cubic yard for superstructure; arrived at by taking the average price of the job and adding $7. to it. This is a liberally high estimatd for the cost of the superstructure and from the resultant platted points on sheet 2 the straight line represents a high and conservative price per cubic yard of superstructure concrete.


SHEET-1.
CONTRACT PRICES
STRUCTURAL STEEL BRIDGES.
ERECTED AND PAINTED.
o - Show Job Contract Number.
Structural Steel - Cents per Pound.
11.
10.
9.
8.
7.
6.
5.
Year - 1918.
1919.
1920
1921
1922.
1923.
1924
Don F. Redick.

SHEET-2.

CONTRACT PRICES.

90' CONCRETE GIRDERS.

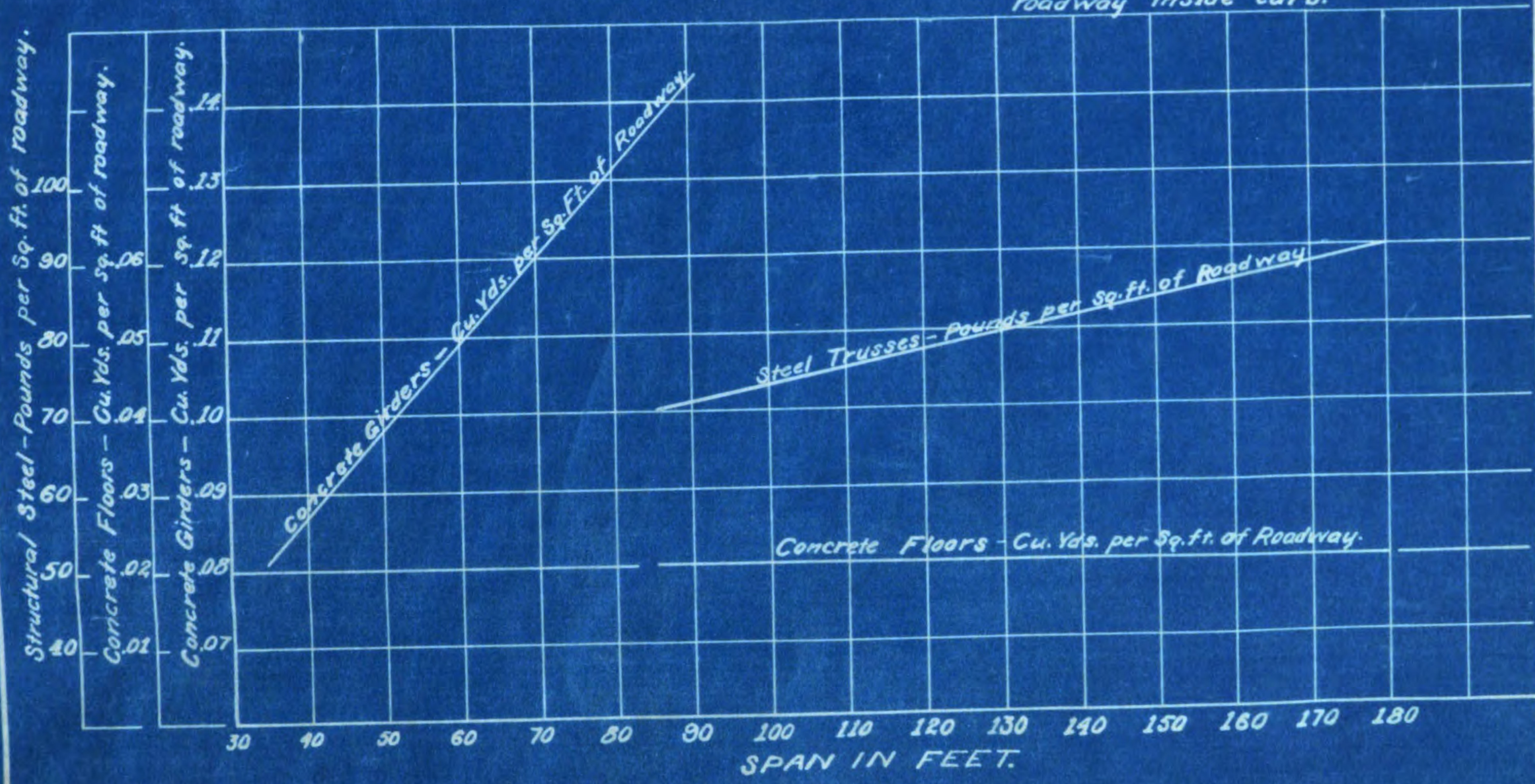


Don F. Hedick.

Don P. Radick.

SHEET 3.
Concrete Girders
Steel Truss Bridges
Concrete Floors.

Note: Units per sq. ft. of net roadway inside curb.



For a 90' span the quantities involved are 1.4 cu. yds. of concrete per sq. ft. of roadway for the concrete girder, 71# of structural steel per sq. ft. of road-way for steel superstructure and .03 cu. yds. of concrete per sq. ft. of floor surface for the concrete floor. Then if "x" represents the price in cents per cu. yd. of superstructure concrete and "y" equals the price of structural steel errected and painted, for a 90' girder, then x equals 668¢ for equal costs. This means that for equal spans with structural steel at 5 cents per lb., the concrete girder might average 30 dollars per cu. yd., at 6 cents per lb. the concrete girder might average $36 per cu. yd., at 7 cents per lb. the concrete girder might be $42.50 per cu. yd., at 8 cents it might be [illegible] per cu. yd., at 9 cents $54.50., and for 10 cents it would be quoted at $60.80 per cu. yd. For a 75' span simiiliar figures would be as follows: Steel per lb. 5¢-concrete per cu. yd.-$34.00. 6¢--$40.80. 7¢-$47.60. 8¢--$54.50. 9¢--$61.20. and for $0¢--$68.00.

Take an example as of Sept.1, $023, sheets 1 and 2, The price per lb. for structural steel as shown on the curve is 8.6¢ For a 90' girder therefore you could afford to pay $52.10 per cu. yd. for superstructure. Referring to sheet 2 it will be noted that actually you could pay $42.50 . This means that if you would build a 90' span of steel, it would cost 22.6% more than to build it of concrete. Going back to Jan.1, 1923, steel prices are 7.1¢ per lb., for which in a 90' girder you could afford to pay $43.10 per cu. yd. for the concrete. From curve 2 we find the actual cost to be $40.50, thus choice would be again in favor of the concrete. Now take the low price of steel in 1921 and it will be noted that one could afford to pay $33.00 per cu. yd. for the concrete superstructure. This price prevailed through the year 1921 and corresponding prices for the concrete ranged from $33.0 to $38.00. This is on the assumption, however, that prices for concrete superstructure are $7.00 per cu. yd. higher than the average price per cu. yd. for the job. This is considered a very conservative allowance.

The above discussion is based on the ratio of first cost of actual superstructure. In addition to the actual saving on first cost due to superstructure there is a saving in the substructure for concrete girders as against steel bridges, which varies with the height of the abutment. This was found to be in the specific example which was discussed near the beginning of this article. The top 8' of the abutment, that is, from bridge seat to roadway is dispensed with in the concrete girder since the girder itself serves to retain this fill. For a steel structure the abutment must be carried to full height of roadway in addition to a very thick section.

In addition to the first cost of structures the matter of maintenance must be considered. Assuming that a steel structure will require a coat of paint every three years and that it will take .5 gallons of paint per ton of steel, the cost would be $1.75 per ton of material. Labor usually runs from 1.5 to 2 times the cost of material, thus making an approximate cost of $5.00 per ton of steel or .25¢/lb. Then assuming an average price per lb. of .6¢/lb. for steel this gives a three year maintenance charge of about 4% for the three year period.

In addition to the first cost and maintenance charges in comparing (comparative) relative values of the two types of structures, attention must be called to the ability of concrete structures to resist increased live loads. For example the 90' girder has .142 cu. yds. of concrete per sq. ft. and weighs 575 pounds. This carries a live load of 100# in accordance with the specifications of design, making a gross load of 675 lbs. per sq. ft. If we now increase the live load or weight of truck using the highways by 50% ●kermat5rlbb.inrtHe4girder would be overstressed merely 50% of 675 lbs. or 7.5% However in this interval the concrete will have increased in strength more than the increase in live load, since the design for concrete is based on 28 days strength and a result in gain in strength from a 28 day to a 12 months period will easily reach 20% for the material. Now had a structural steel design been used, it would take 71 lbs. of structural steel and 80 lbs of concrete floor or a total of 151 lbs. per sq. ft., carrying a load of 100# per sq. ft. or a total load of 251# per sq. ft. If with this structure the live load is increased 50% the stresses would be exceeded by an amount equal to 50% of 250#, or 20% as compared with 7.4% for the concrete design. In steel there is no gain in strength but rather a loss due to age.

In the matter of durability, no one can say what the life of good concrete is. No experienced person will attempt to say, but any concrete engineer will admit, the life of a concrete structure is as long as the life of a steel structure other things being equal. The matter of the life of a structure in this day and age of rapid changes is not the determining factor since the increases in width of roadway, load capacities, and the whim of thepublic in regards to appearances and aesthetic treatment are much more vital features and imply that most of our structures will be removed before they are worn out.

The design of reinforced bridges for 70' to 90' span have curved top chords and bottom chord brackets. The first 90' girder span was completed at Tecumseh, Mich. Now some notably long spans and difficult structures are to be seen under construction. The state has on several occasions tested some 90' girders and found them exceptionally stiff andremarkably free from impact and and vibration. The unit stresses are well below those

for which the structure was designed. The department of bridges is experimenting with long spans and expects to replace 100' to 150' steel spans with concrete trusses. This tends to obviates the difficulties and long time contracts resulting from the handling of substructure, superstructure, and floor contracts and still keep within the limits of true economy. The advantages of having a single contractor, using common and readily securable materials, and the resulting rigidity and large inertia with consequent ability to absorb impact and live load increases with but small overstresses are highly desirable.

The policy of the state of Michigan tends largely toward concrete design. Bractically 90% of the bridge bridge construction in that state being of that type. It has been there found profitable to use concrete up to a point where the first cost of the concrete may be 10% higher than the first cost of steel, due to the fact that maintenance of steel is high and also annual depreciation is greater on the steel structure. During the past two years the bridge department has eliminated a great percentage of the steel bridges formerely in use by extending the concrete girder design to and including 90' spans. Now practically no consideration is given to steel construction below 100' spans.

However steel bridges are not without arguements for their use entirely. A few of the arguements that seem to be in favor of steel as a bridge superstructure may be found in the following paragraphs obtained from consultations with men interested in the construction of steel bridges as a profession.

The concensus of opinion seemed to be in favor of concrete construction for beauty and aesthetic treatment but this point is not one of considerable importance.

The points which should control the general design of a bridge as most folks seemed to agree were:

1. Physical conditions of the sight.

2. Requirements of the traffic.

3. Requirements of the purchaser regarding type, ornamentation, and special treatment.

4. Money available.

It is maintained that a steel superstructure can be put on a cheaper foundation than can a concrete superstructure. The type of abutment and footing designed by the state department are not the most economical for the service required of them in maintaining a steel superstructure. In cases where a bridge is being built over a sink hole, or in places where the soil is unstable and uncertain a steel superstructure is more certain to prove satisfactory because a slight settlement, if one should

occur, would do no harm to the steel superstructure whereas it might ruin a concrete design.

Types of bridges are being changed continually to meet new requirements. In this connection it is to be noted that of a total of 366 bridges put under contract to date 148, or about 40.5%, have been of 18' roadway. Very few bridges are now being built with 18' roadways. Practically all of these bridges mentioned are less than ten years old but still many are being torn out in favor of the 24' or other width roadways. This tends to show that it is unnecessarily wise to spend large sums of p public money to provide for the future 75 or 100 years hence. No one knows what traffic conditions will be then.

Up to the present time practically all of the highway bridges have been constructed with roadways of 24' or less. It is rumored that within two weeks previous to the present writing the Governor of the State of Michigan directed the bridge engineer for the state to start changing all bridge plans and provide for roadways of from 30 to 36 feet on all future bridges. This move will make obsolete all of the expensive massive structures designed by the state so far as state work is concerned. Who knows how long these new structures will adequately serve the public need. Why, then, try to provide for a distant, uncertain future when chances are large that the structure will never serve over half of its contemplated life.

In the case of steel bridges, when it is desirable to relocate a stretch of road, asis often done,and a steel bridge is located on the abandoned portion of the road it can easily be moved to the new bridge site or somewhere else and put to use. In the case of a concrete bridge it would have to be abandoned entirely or else removed at a considerable expense.

A steel structure over a drain or river can be remover from the abutments and permit a dredge to pass through if the bed is ever cleaned out or deepened. Also the guard rails on a beam bridge can be removed to allow wide oblects such as houses, barns, etc to pass over when being moved.

In regard to steel bridge work not being satisfactorially done it is certain that the states engineers are on the job with the instructions to reject any part or all of the work if it is not properly done. All finished work must have their approval before any money can be collected on the job.

As a matter of unsettled arguement, which can only be settled by reference to the records, it is maintained that the substructure, superstructure, and floor are all usually let in one contract whether the job calls for concrete or steel superstructure. The matter of sub-contract is optional with the purchaser hence the argument that delays due to hold-ups on one or more contracts seems weak.

At present it is the policy of most organizations that are purchasing bridge structures to investigate what a nearby railroad has done over the same stream near by in regards to length of span and clearance. This is done to get the advantage of the experience of the railroads. Their engineers are regarded as among the best in the country. Nearly all of the bridges within a reasonable length of span that are built by the railroads are of the plate girder type. If the railroads find the plate girder superstructnres will stand the vibrations and impact, and can give satisfactory and economic service, wouldn't they be worth consideration for use on the highways? With the prices that prevail in Michigan in 1925 plate girder highway bridges can be sold, errected and painted, for 8¢ per pound. A plate girder highway bridge may not present as pleasant a view as a concrete girder; but in the light of economy and good business it is hard to believe that the aesthetic treatment is worth the difference in cost, difference in the length of time that the road is closed during construction, ease with which the exact status of the bridge can be determined, and simplicity of construction.

In conclusion the author wishes to state that a comparative analysis of steel and concrete in structures made today would be of little use 10 years from today, because of the ever changing ratio of prices, methods of handling and transporting materials, and changes in the demands made upon the structure in its uses. For example:A bridge built during the war was considered best when it required the least labor and time for construction but which would gave promise of serving for a reasonable length of time. Today that bridge is best which presents the the most pleasing view when seen in the surroundings in which it is to be constructed. In other words aesthetic treatment seems to have the greatest bearing on the type of bridge chosen. What features will control the design of bridges 10 years from today noone can tell.

The writer commenced his investigations for this thesis with a prejudice favoring steel superstructures for use on bridges on the public highways. This prejudice was the result of a lack of knowledge of the adaptability of the concrete superstructure when used under the varying conditions that a bridge for standard use would be applied. After concluding what was considered an impartial investigation the writer has concluded that for highway bridges that must continually bear increased loadings and serve the greatest possible length of time a concrete girder is the most economical type up to and including spans of 100' in length. Enough data is not available to make an accurate comparison of spans of greater length. Rough estimates indicate, however, and the writer is inclined to agree, that for the longer spans steel structures are the most economical.

Data for this thesis was taken from a survey of the records of the bridge department of the State of Michigan, advice of friends, and from consultations with contractors, steel manufacturers, and others interested in the subject.

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