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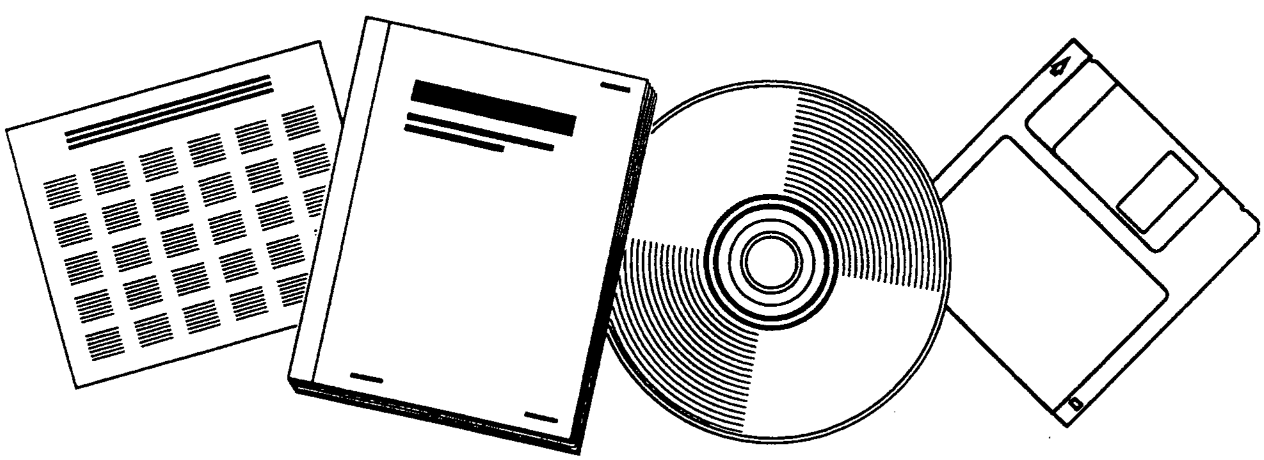

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Strength Criteria For Cast-Iron Items In Highway Drainage Structures

RUIJIA MU
SREENIVAS ALAMPALLI

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STRENGTH CRITERIA FOR CAST-IRON ITEMS USED IN HIGHWAY DRAINAGE STRUCTURES

Ruijia Mu, Civil Engineer I
Sreenivas Alampalli, Engineering Research Specialist II

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New York State Department of Transportation
State Campus, Albany, New York 12232-0869

ABSTRACT

In modern foundries, manufacture of cast-iron objects for drainage structures (manhole covers, drainage grates, etc.) has been automated, with improved techniques and equipment enabling manufacturers to cast these items to closer dimensional tolerances, thus reducing wall thicknesses and overall weights without sacrificing durability or performance. Because their cost is generally proportional to weight, lighter items thus may result in significant savings. Current standard designs were adopted many years ago -- their sources are often unknown. This report reviews pertinent standards, discusses methods used in procuring cast-iron items by several transportation agencies, and recommends new acceptance criteria based on proof-load testing.

CONTENTS

Figure 1. Typical cast-iron drainage items include manhole frame and cover (upper left), curb frame for inlet grate (upper right), grate and frame installed flush with pavement surface (lower left), and rings to raise manhole covers after pavement overlay (lower right).

INTRODUCTION

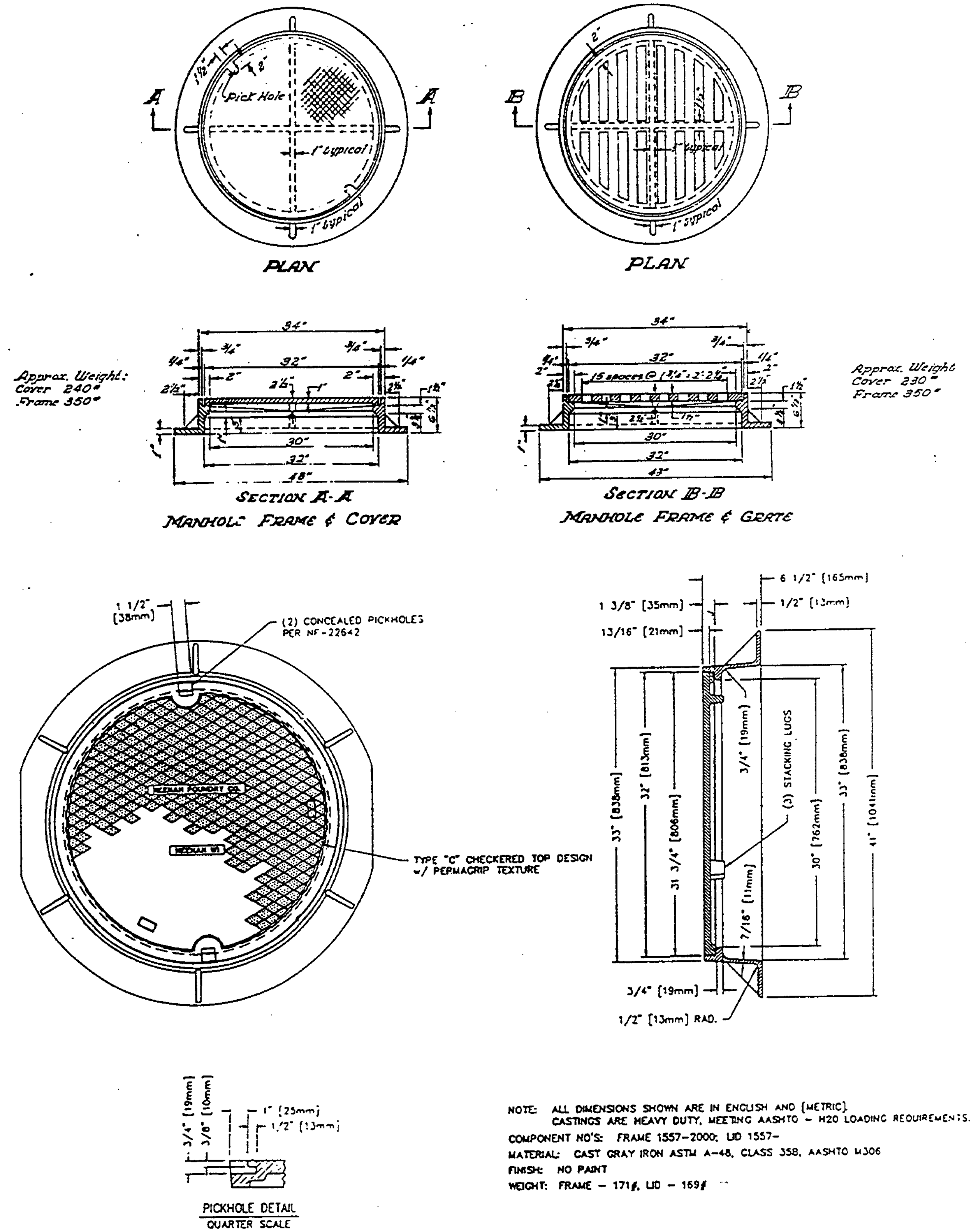
Drainage structures include numerous cast-iron items in their construction. Manhole and inlet frames, covers, grates, and rings are almost exclusively fabricated from cast iron (Fig. 1). Historically, cast-iron patterns and fabrication involved processes relying largely on manual labor. The standard industrial material for construction castings has been gray cast iron, prone to such manufacturing defects as small holes and voids. Due to this high variability in quality of material and workmanship, high safety factors have been considered necessary in designing and accepting cast-iron items. For example, even though minimum tensile strength for New York State's gray iron casting for AASHTO/ASTM Class 30B has been specified as 30 ksi (207 MPa) (*1*,*2*), AASHTO's *Standard Specifications for Highway Bridges* (*3*) limits maximum allowable bending in extreme fiber and shear stresses to 3000 psi (20.7 MPa), giving a safety factor of 10.

Due to technological developments in recent decades, as well as the Clean Air Acts and related regulations of the 1960s, manufacturing processes for cast iron have been streamlined and subjected to better quality control. In modern foundries, automated manufacturing of cast-iron articles with improved techniques and equipment enables manufacturers to cast to closer dimensional tolerances. Wall thicknesses and weights have been reduced, but the castings produced are as strong as thicker, heavier designs produced with older equipment and processes. Most states, including New York, adopted their standard sheets for cast-iron items many years ago, and their origins and rationale often were not documented. Experience has shown their performance to be adequate, but these items have probably been stronger than required and thus more expensive than necessary. Also, patterns for these designs may not have been economical.

Figure 2 compares a typical New York State manhole cover (*4*) with one now proposed by a commercial foundry company (*5*). On traditional standard sheets, wall thicknesses of 3/4 in. (19 mm) or more are common. For the new products, wall thickness can be reduced to less than ½ in. (12.7 mm). Total weight of a frame and cover is about 600 lb (272 kg) for the traditional design, but less than 350 lb (157 kg) for the new product..

Currently, New York State has no specifications for structural design of these items. Because cost of cast-iron items depends largely on how much material is used, new designs with reduced weights will result in significant savings. At present, their is no objective manner in which an average working engineer can design or evaluate designs by others for these items. Due to conservatism of infrastructure owners, continued use of stronger, more expensive items with good in-service histories is likely. However, if acceptance criteria are developed to evaluate new designs, great savings may be achieved. In 1995 alone, New York State awarded almost $3

Figure 2. Details for typical manhole covers from New York State standard sheet (top) and as proposed by vendor of cast-iron products (bottom).



million for three construction pay items for castings or steel grates in cast-iron frames. A modest reduction of 20 percent in weight might result in $500,000 annual savings in New York State alone. Thus, great economies may occur if items weighing less are found to be acceptable.

The objective of this report is to evaluate existing procedures used by various transportation agencies to design cast-iron items, and to suggest acceptance criteria for government agencies for items having new patterns. At the request of the Design Quality Assurance Bureau, procedures used by New York were thoroughly examined, and pertinent specifications and test programs from various manufacturers were studied. A questionnaire was sent to other state and Canadian provincial transportation agencies to determine procedures used elsewhere to design and accept these items. Finally, a set of acceptance criteria based on proof-load testing is recommended. This report describes that study and its recommendations.

1. REVIEW OF CURRENT DESIGN PROCEDURES

A literature search revealed few pertinent references concerning design of cast-iron devices. No information is available on designing them, but some code requirements exist for strength control. Five major existing codes include AASHTO specifications, federal specifications, and a European standard. Their strength requirements are summarized here.

"Standard Specifications for Drainage Structure Castings" (AASHTO M 306-89)

This standard (*6*) applies to frames, grates, rings, and covers for inlets, manholes, and other structures for civil-engineering use where tensile strength is a major consideration, with these provisions:

1. Materials for iron castings must conform to "Gray Iron Castings" (AASHTO M 105/ ASTM A 48, Class 35B).

2. Manufacturing must conform to Federal Specification RR-F-621C.

3. Frames and covers must show no permanent deformation when a proof load of 40,000 lb (18.2 Mg) concentrated on a 9- by 9-in. (230- by 230-mm) contact area is placed on the cover or grate of the drainage-structure casting. Load must be applied by a suitable testing machine and held for a period of 1 min. Upon its removal, for acceptance the cover or grating and frame must not show any cracks or permanent deformation.

4. An alternative load testing is given for inspection test bars subjected to tensile testing.

"Standard Specification for Gray Iron Castings" (AASHTO M 105-94/ASTM A 48-94a)

This specification (*1,2*) covers gray iron castings for general engineering use where tensile strength is a major consideration. A minimum tensile strength of 35 ksi (241 MPa) in bar testing is required for Gray Iron Castings Class 35B, and 30 ksi (207 MPa) for Class 30B.

"Cast Iron" (AASHTO Bridge Specifications Item 10.32.5.3)

This item (*3*) limits allowable stresses for cast iron in bending in extreme fiber and shear to 3000 psi, and also must withstand HS20 loading (a wheel load of 16 kips). Cast-iron castings must conform to specifications for gray-iron castings: AASHTO M 105/ASTM A 48, Class 30B (*1*,*2*).

"Frame, Covers, Castings, Steps, Sump and Catch Basin Manhole" (Federal Specification RR-F-621E)

This standard (*7*) is for use by all federal agencies, covering manhole and catch-basin frames, gratings, sumps, and catch basins for access purposes. It suggests a minimum 25,000-lb transverse proof load, when used under traffic loads, for frames, covers, gratings, steps, sump and catch basins, and manholes. For acceptance, no evidence of cracks or permanent deformations may be found after test. As a minimum, test cast-iron castings must conform to requirements of gray-iron castings Class 30B.

"Gully Tops and Manhole Tops for Vehicular and Pedestrian Areas: Design Requirements, Type Testing, Marking, Quality Control" (European Standard EN 124)

This standard (*8*) applies to gully tops and manhole tops with a clear opening up to and including 1000 mm for installation within areas subjected to pedestrian and/or vehicular traffic, to tested as complete units in their condition of service. For those with clear openings of 250 mm (10 in.) or more, the test load is 400 kN (90,000 lb) for Class D400 (road carriageways). Load must be applied at a rate of 1 to 5 kN/s up to two-thirds of the load. Permanent set at the geometric center of the cover or grating may not exceed 1/300 or 1/500 of the clear opening, depending on method of securing the cover within its frame. At end of test, the test load should be maintained for about 30 s. For acceptance, the item must not show any cracks during the test. Cast-iron castings must be made from flake-graphite or spheroidal-graphite cast iron.

SURVEY FOR CURRENT TRANSPORTATION AGENCY PROCEDURES

In addition, a questionnaire was sent to all state and provincial transportation agencies and several foundry companies for information on design procedures and basis of acceptance, factors used in design, dimensional tolerances, failures, and on-going research for cast-iron items. A total of 26 responses were received, and showed that the states or provinces generally do not design their own items. State and provincial agencies either rely on manufacturer's designs and recommendations or have some standard details with the basis for design unknown. Survey results for strength are summarized in Table 1.

Table 1. Survey results for strength requirements*.

Organization	ASTM A 48/A536	AASHTO M 105	AASHTO M 306 (40-kip proof-load)	Federal Specification RR-F-621E (25-kip proof-load)	Manufacturer's Recommendation	Standard Sheet (basis unknown)
Alabama DOT		Yes	Yes			
Arkansas DOT						
Caltrans	Yes			product inspection only	Yes	
Connecticut DOT					Yes	
D.C. DPW			Yes			Yes
Georgia DOT			Yes			
Iowa DOT			Yes		Yes	
Kentucky DOT					Yes	
Manitoba Highwys & Transportation						
Maryland DOT	Yes		No			Yes
Mn/DOT			Yes		Yes	
Montana DOT			Too high	Yes		
Nebraska D.O.R.			Yes		Yes	
New Hampshire DOT		Yes	Probably			
New Jersey DOT		Yes			Yes	Yes
Nova Scotia DOT			Yes			
Ohio DOT	Yes		Not required, to be adopted		Yes	
Oregon DOT	Yes	Yes				
PennDot			Yes (50 kips)			
South Carolina DOT		Yes	Too high	Yes		
Texas DOT					Yes	
West Virginia DOT						Yes
Neenah Foundry Co.	Yes	Yes	Yes			
South Bay Foundry	Yes		Yes	Yes		
Syracuse Castings	Yes	Yes				Yes
U.S. Foundry	Yes	Yes	Too high	Yes		

*Information is based on answers to survey questionnaires and telephone conversations with respondents. When information was not available, entries are left blank.

In a majority of responses, AASHTO M 306 is identified as principal authority not only for materials specifications, but also for performance specifications. Based on the authors' conversation with the Technical Section Chair of the AASHTO Committee on Drainage Structure Castings (*9*), although its basis is unknown, the 40-kip (18.2-Mg) proof-load test that AASHTO recommends appears to have been intended for strength control of all products, including those with new designs.

2. TECHNICAL ISSUES RELATED TO DESIGN OF CAST-IRON ITEMS

Based on information obtained from studying available specifications and the survey responses, six technical issues should be noted as heavily influencing design of cast-iron items: 1) allowable stresses, 2) safety factors, 3) stress-analysis procedure, 4) fatigue, 5) impact, and 6) deformation. These are now discussed in terms of recommendations for design as developed in this study.

Allowable Stresses

AASHTO's highway bridge specifications (*3*) specify 3000 psi as allowable stress for bending in extreme fiber and shear, but the survey indicated that transportation agencies are not using that recommendation. Foundry companies said that no current products meet that requirement. According to simplified hand calculations and finite-element analysis by one producer (*10*), products based on current specifications of the New York State Department of Transportation also do not meet that requirement. Under a 16-kip service load, stresses on these covers are at least three times higher than 3000 psi. The fact that none have ever failed due to insufficient strength shows that this allowable stress is too conservative. It is believed that these stresses were not meant for use in manhole-type structures, but rather intended for bridge design where cast iron is used for main load-carrying members, including both dead and live loads.

Safety Factors

Minimum tensile strength of gray iron castings Class 30B is 30 ksi. An allowable stress of 3000 psi would imply an equivalent safety factor of 10 -- in steel design, safety factors are normally in the range of 1.5 to 2.5. A proof load of 40 kips for a standard 16-kip wheel load means a safety factor of 2.5, including impact factor. When allowable stress is specified for a member design, a larger safety factor may be needed to account for possible stress concentrations and other factors, but when a product is tested as a complete unit, a smaller safety factor is acceptable.

Stress Analysis Procedure

Because of the complex geometries of cast-iron items, stress analysis is generally complicated for these structures using either finite-element analysis or hand calculations. Results may vary considerably, depending on modeling details and experience of the analyst. Further, some special aspects must be considered for cast iron -- for instance, modulus of elasticity is not constant and is higher in compression than in tension. Consequently, using standard structural formulae results in conservative design (*11*). Accurate stress analysis thus is not generally required for cast-iron items, although it should be encouraged to optimize design. Final products should be required to pass full-scale load tests.

Fatigue

Because such structures as manhole covers are subjected to repeated traffic loads, the fatigue problem must be considered. Maximum stress that will allow infinite cycles of loading is defined as the endurance limit of the material. Dividing this limit by the maximum tensile strength gives the materials's endurance ratio. For iron castings under half-cycle bending/torsion loads, endurance ratios between 0.4 and 0.6 have been reported by various investigators (*11*). Thus, if working stresses on a casting do not exceed 40 percent of ultimate stresses, an infinite fatigue life might be expected. A 2.5 safety factor in the proof-load ensures that working stresses are within 40 percent of ultimate stresses. Thus, if a cast iron product passes proof-load tests, it should have infinite fatigue life under normal service loads.

Impact

Impact resistance of cast iron is generally much lower than for other metals. Installation of gray iron in drainage structures often involves impact loads. It is important to ensure that iron offers sufficient toughness for satisfactory use. Cast iron usually allows fracture to occur with very little plastic deformation. The principal energy absorbed in fracture thus is the elastic energy stored as the specimen is stressed to the level where fracture occurs, as shown in Figure 3. An engineer at the Neenah Foundry Company of Neenah, Wisconsin (*12*) recommends that maximum absorbed energy be used as an index for the impact resistance of manhole covers. According to the *Iron Casting Handbook* (*11*), ability of gray iron to resist impact loading can generally be related to tensile properties of the iron. To consider impact loads, data for dynamic tear tests show that a stress equal to 50 percent of ultimate tensile strength may be used as a design parameter for static loading. AASHTO bridge specifications (*13*) take impact into account by increasing the design live loads. The maximum amount of the impact increment is 30 percent for bridge superstructures. Considering that traffic loads are always applied through wheel tires, a 30-percent increase (rather than 100 percent) is suggested as the impact allowance for cast-iron items in drainage structures.

Deformation

Although cast iron is considered a brittle metal, it is believed capable of deforming permanently by a measurable amount. Figure 4 shows appreciable plastic deformation for cast iron at stresses

Figure 3. Energy absorbed related to strain and stress.

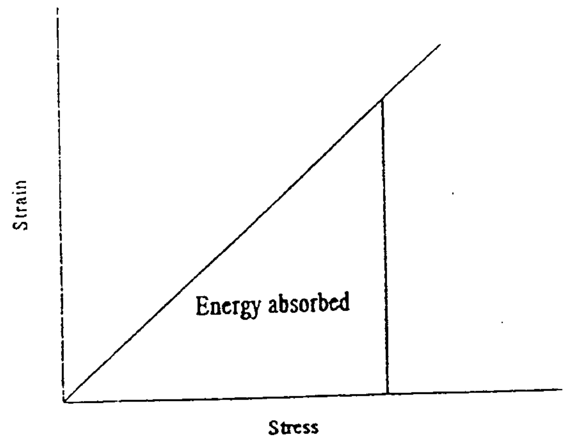
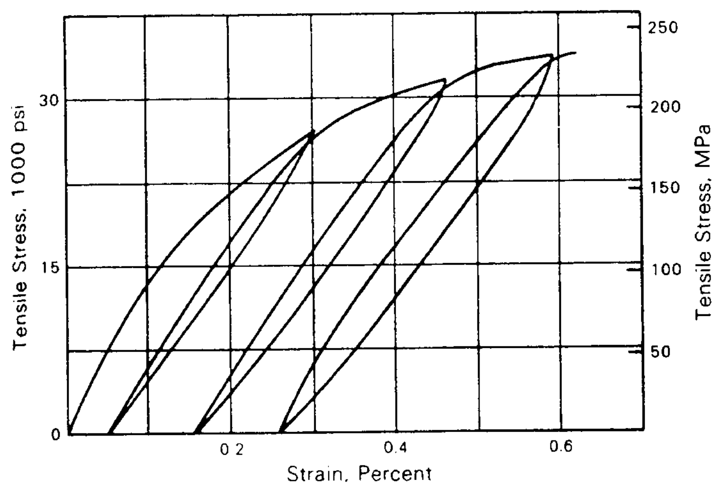


Figure 4. Stress-strain curve in tension for Class 30 gray iron, with load removed to show permanent deformation [Fig. 19 from *Iron Castings Handbook* (*11*)].



above 75 percent of ultimate strength. The Neenah foundry engineer indicated that 1/8 in. is used as a maximum allowable deformation for his company's proof-load testing -- the maximum permissible variation of dimensions specified by AASHTO. Similarly, the Syracuse Casting Sales Corporation (*14*) suggests maximum allowable deformation of 1/150th of the span, which is now used for some other applications. In European Standard 124, permissible permanent set after applying two-thirds of a test load is 1/500th of the clear opening for Class D400, when a manhole cover is secured within its frame by self-weight. Thus, "no permanent deformation" seems to be inappropriate at the end of a proof-load test for the acceptance level suggested by AASHTO.

3. RECOMMENDATIONS FOR STRENGTH CONTROL

Substantial amounts are spent for cast-iron items. Along with the rising price of cast-iron scrap, this warrants that the engineering community to develop design and acceptance procedures providing the same degree of confidence and guidance as for such structural components as steel grating. As just noted, due to the complex geometries of cast-iron items, stress analysis is generally complicated, whether using finite-element methods or hand calculations. Thus, developing design procedures based on theoretical concepts is tedious. Finite-element analysis as a basis for design is complex and intensive -- results lacking proper calibration are very subjective, depending on the modeling procedures used. In the absence of standardized design and analysis procedures, proof-loading with a comfortable safety factor can be used for acceptance of cast-iron objects, providing a means for evaluation of new designs and the quality of products offered by new vendors.

Based on the issues raised here, the following recommendations are suggested for acceptance of cast-iron items in New York State. All cast-iron items (frames and covers used in manholes, drainage structures, and pull boxes, etc.) should meet the requirements of AASHTO M 105 and M 306, with the following modifications in proof-load testing, effective until further information is developed:

1. Products should be tested as complete units, including frames and covers, in their service condition. If they are to be subjected to traffic loads, the proof load should equal the design wheel load multiplied by an impact factor, and times a factor of 2.5. Using a 16-kip wheel load as the design load and an impact factor of 1.3, a proof load of 52 kips (230 kN) is recommended. If products are designed for other loads, proof load should be adjusted accordingly.

2. As specified in AASHTO M 306, the proof load should be held for 1 minute. Upon its removal, the cover and frame should be examined for cracks or permanent deformation, "No permanent deformation" is defined as less than 1/8 in. or 1/150th of the clear opening, whichever is smaller. Test setup and sampling should follow AASHTO M 306.

3. In examining a new product design, it is suggested that a minimum of five samples be selected at random for proof-testing. If failure occurs in any test, and is not caused by an observable manufactured defect, the design should be considered structurally inadequate. As more test data become available, total number of tests may be modified.

CONCLUSION

A study was undertaken to review design procedures now used for cast-iron items used in drainage structures. Pertinent specifications were reviewed and related technical issues studied and discussed. In the absence of standard design and analysis procedures, new criteria are recommended for acceptance, based on proof-load testing. This method offers means to evaluate new designs and the quality of products offered by new vendors, with potential for significant savings for owners.

ACKNOWLEDGMENTS

Several staff members of the New York State Department of Transportation were consulted, and discussions with Dr. Robert J. Perry, Director of Transportation Research and Development, and Larry Brown of the Design Quality Assurance Bureau were particularly useful. Cooperation of the Neenah Foundry Company of Neenah, Wisconsin, and the Syracuse Castings Sales Corporation of Cicero, New York, is greatly appreciated.

REFERENCES

1. "Standard Specification for Gray Iron Castings." AASHTO Designation: M 105-94, *Specifications for Materials*, American Association of State Highway and Transportation Officials, 1992, pp. 96-103.

2. "Standard Specification for Gray Iron Castings." ASTM Designation: A 48-94a, *ASTM Book of Standards*, Vol. 01.02, 1994, pp. 15-24.

3. "Cast Iron." Item 10.32.5.3, *Standard Specifications for Highway Bridges*, American Association of State Highway and Transportation Officials, 1996 (16th ed.).

4. "Reticuline Type Grates and Frames and Manhole Covers, Grates and Frames." Standard Sheet 655-3, Structures Design and Construction Division, New York State Department of Transportation, 1973.

5. "R-1557, Frame and Type 'C' Platen Lid." Neenah Foundry Company, Neenah, Wisconsin, 1995.

6. "Standard Specification for Drainage Structure Castings." AASHTO Designation : M 306-89, *Specifications for Materials*, American Association of State Highway and Transportation Officials, 1992, pp. 645-46.

7. "Frames, Covers, Gratings, Steps, Sump and Catch Basin, Manhole." Federal Specification RR-F-621E, February 23, 1989.

8. "Gully tops and manhole tops for vehicular and pedestrian areas -- Design requirements, type testing, marking, quality control." European Standard EN 124, 1994.

9. Telephone conversation with Eldon D. Orth, Engineer, Materials & Tests Division, Nebraska Department of Roads, October 1996.

10. "Analysis of Round Manhole Cover with Round Symmetrical Loading and Simply Supported Edges Using the Proof Load Test Specifications." Syracuse Castings Sales Corporation, Cicero, New York, 1996.

11. Walton, C.F., and Opar, T.J. (eds.). *Iron Castings Handbook Covering Data on Gray, Malleable, Ductile, White, Alloy and Compacted Graphite Irons*. Rocky River, Ohio: Iron Castings Society, Inc., 1981 (3rd ed.).

12. Telephone conversation with Steven Akkala, Manager - Product Engineering, Construction Division, Neenah Foundry Company, Neenah, Wisconsin.

13. "Impact Formula." Section 3.8.2, *Standard Specifications for Highway Bridges*, American Association of State Highway and Transportation Officials, 1996 (16th ed.).

14. Memorandum dated 6/20/95, titled "Design procedures for cast iron articles. (Memo dated 5/13/96)," from Mark Pulver, Syracuse Castings Sales Corporation, to Larry Brown, Design Quality Assurance Bureau, New York State Department of Transportation.

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