PRESTRESSED HIGHWAY BRIDGE REHABILITATION BY EXTERNAL PRESTRESSING

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Abstract

Many bridge structures were designed across the Vah river. The method of reconstruction one of such highway bridge from prestressed concrete is presented in this paper. This bridge is located in the Northern part of the Slovak Republic near by Bytca town . New condition of channel operation, diagnostic inspection of bridge, long term measurement of deflections and control load carrying capacity (LCC) calculation constitute the major background for design of bridge rehabilitation. Some type of repairs have been performed in order to improve the bridge condition and to increase service life. Strengthening of superstructure by external prestressing was finally selected as a way to increase loading capacity.

1. INTRODUCTION

A lot of new channels were built-up on the Vah river in Slovakia during 50. – 60. years. It had been required to build-up new highway diversions with new bridges across the channels of Vah. There was realised more types of bridge structures as steel plate girders, truss girders, reinforced concrete continuous beams, precast prestressed bridges and frame monolithic structures.

These bridges have common attributes in spite of some differences :

Many of them were realised before channel building on the "green field", that was more simple and convenient from building technology point of view. But from present view of maintenance and eventual reconstruction works it hasn't seem to be so lucrative. First of all considerable permanent deformations were detected on more concrete monolithic bridges due to formwork declining within concreting process. The deterioration of these bridges has very similar character and the knowledge level of that time being issued in. The next observed failure is caused of bad quality of bridge accessories - bituminous overlay and waterproofing membrane, expansion joints, drainage system, etc. Degradation process in concrete, corrosion in reinforcement or prestressing cables have been resulted such failures. These processes together with next ones as the concrete creep and shrinkage, overloading by live load, etc. have caused crack formation in superstructure and extraordinary permanent deformations.

It is necessary to take in to account the particular requirements due to channel operation, except ordinary ones for complex design of bridge rehabilitation. The service on channel cannot be disturbed with building activity. The abutments of new bridge structures have to be located in certain distance from base of the earthworks. It have been issued to large span bridges (channel dimensions). There is allowable no invasion or minimum invasion to cross section of channel within reconstruction works. In addition new waterway will be suggested in that channel. Regarding to this the demand of free shipping high between water level and bottom edge of superstructure must be complied. Therefore also the design of reconstruction have to fulfil this conditions.

The design method of prestressed bridge rehabilitation with any above mentioned typical failures is presented in this paper. Insufficient load carrying capacity was investigated too, in order to present requirements in our standard (Slovak standard STN 73 6203). Department of Building Structures and Bridges of University of Zilina was requested to collaborate with that problem.

2. DESCRIPTION OF BRIDGE STRUCTURE – ORIGINAL DESIGN

The bridge is built on highway connecting two little towns on both sides of channel. It was designed in 1959 for load classification "A" according to available standard. It is one span direct structure with perpen-

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dicular vertical alignment. Disposition on the bridge is both-sides pavements - 1,0 m width and roadway - 6,0 m width, see the Fig.1.

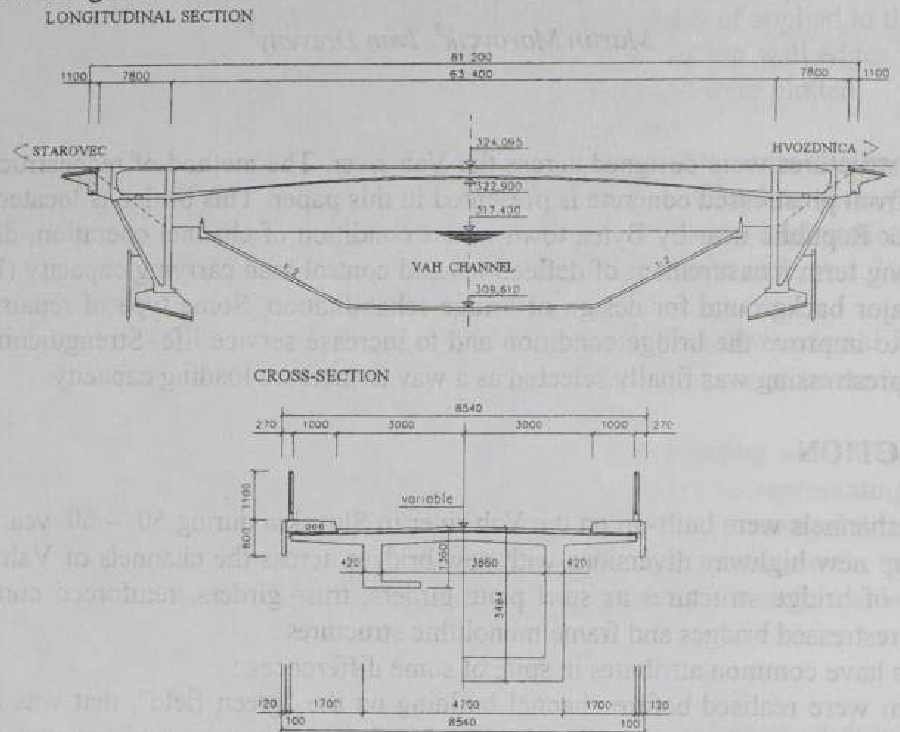

Figure 1. Hvozdnica Bridge. Longitudinal and Cross Section.

Structural system is composed of prestressed two-hinge frame with ties in ending parts of bridge. The span is 63,40 m and frame girder is parabolic profile from 3,42 m over the abutment to 1,26 m in the centre of the span, see the Fig. 1. That means the span/depth ratio is 50,3. Cross section of superstructure is box girder shape. Monolithic deck slab and webs are constant depth. Superstructure is built from concrete with a cube strength of design value 37,0 MPa, C30/37. Prestressing was realised by tendons consisted from 17 wires ϕ P4,5 mm with strength characteristic f_y / $f_{0,2}$ = 1650 / 1200. Abutments are composed as triangular system. Vertical webs support the girder by concrete notch hinges. Cantilever part of girder is joined with basement by skew prestressed concrete tie. 48 tendons 17 ϕ P4,5 mm is built-up in that tie. The subsoil is good quality from graded aggregate.

3. ACTUAL CONDITION OF THE BRIDGE

The actual condition of the bridge was determined by diagnostic inspection which includes :

- detailed visual inspection,
- in-situ testing of cube strength of concrete,
- concrete carbonation level,
- chloride penetration to concrete,
- the quality of existing prestressing tendons (corrosion).

Typical deterioration and damage were observed on the bridge structure. Some of them are caused by insufficient drainage system on the bridge. Waterproofing membrane was damaged so that water passes trough the crack in the slab. The main failure on the superstructure is visible large deflection of 187 mm due to supposed decided influence of concrete creep and steel relaxation. This deformation negative effects to dynamic structural behaviour. The cracks approximately 0,7 mm width were observed just in bottom slab in middle cross section on the 10 m length. Concrete strength corresponds with proposed value. Carbonation achieved the level 18 – 54 mm. The chloride content in concrete 4-time exceeded the value compare to allowable standard value for prestressed bridges. Local corrosion appearance was found out due to insufficient concrete cover.

Following goals were formulated : to eliminate all defects and their causes on bridge structure, to retain present clearance of length, to fulfil the conditions of channel regime, and to increase present load carrying capacity that are: normal load carrying capacity = 12,0 tonnes at least to 26,0 tonnes and exclusive load carrying capacity = 17,0 tonnes at least to 50,0 tonnes.

4. REHABILITATION AND STRENGTHENING OF THE BRIDGE

Conception of Reconstruction Works

The rehabilitation of the bridge can be proposed if only traffic will be interrupted in order to type and extent of repair work. The reconstruction works will be performed as followed :

- demolition works - removing all damaged parts of the bridge and consecutively creating of new elements for strengthening as they are deviators, struts, anchorage blocks and strengthening of existing cross beams, see Fig. 2,
- strengthening of box girder by external unbonded cables – to achieve requested value of load carrying capacity,
- to realise all repair works as removing concrete cover, new waterproofing application and removing next damaged elements of bridge accessories,
- during rehabilitation works on the bridge will be necessary to perform deformation measurement in decisive phases : at first before all works starting, than in prestressing process, the next after all permanent load application, and finally proof-load test executing to check the structure resistance to live load effects.

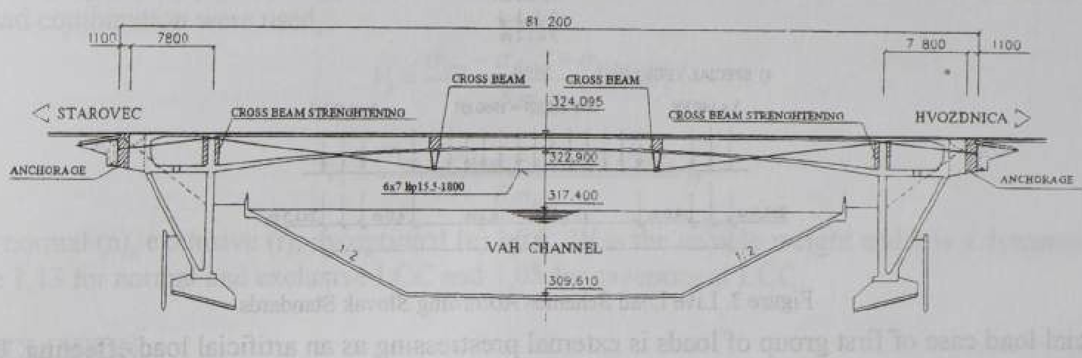

Figure 2. The Conception of Bridge Rehabilitation

Strengthening of the Superstructure

The main goal of superstructure strengthening has been increase load carrying capacity to requested values. Two alternatives were designed : 1) to change bridge performance to stay cable bridge with new pylons creating, 2) applying external unbonded prestressing placed out of box girder, and lifting effect of cables is used. Considering both of alternatives the second one was chosen as final. It has appeared to be more advantageous compare to first method from simple and verified technology, less building cost and speed of installation point of view. Cables consisting from 6 tendons 7 ϕ Lp15,5 – 1800 MPa were designed to strengthening of structure. The steel strut frames were designed as deviators with 1,80 m depth, see Fig 2. Problem of interference to the space under bridge (supposed shipping space) was consulted with Regional Channel Administrators.

Results of diagnostic inspection, long-term measurement of deflections and original project documentation of all internal tendon distribution were used as a background to structural analysis of strengthened structure. Computer program *FEAT* (program of SCIA scientific application group), based on finite element method was used for solving that problem. The elastic material behaviour is considered. because of relative sufficient internal prestressing being active. That keeps the sections in quasi-elastic status. Beam model was used to global load effects simulation, regarding to variable construction depth of superstructure, complicated stresses behaviour (internal and external prestressing) and many load cases and their combinations. Concrete structure (superstructure, abutments) were modelled using beam elements with bending and shear stiffness and simple strut and tie elements with axial stiffness for external tendons modelling.

The load cases were divided to 3 major groups. 1) dead load – self weight of construction including effects of internal and external prestressing and the other long term loading (i.e. bridge accessories, ...), 2) live load according to the Slovak standard [1], where 4 load schemes being applied, see Fig. 3. The first and second load schemes represent vehicles with weight limit 32 tonnes (normal LCC), the third load scheme represents one vehicle with weight limit 80 tonnes (exclusive LCC), and the last one represents special vehicle with weight limit 196 tonnes (exceptional LCC), 3) accessory load case is composed by linear non-uniform temperature gradient that is considered for bridges with span more than 50 m according to our standard.

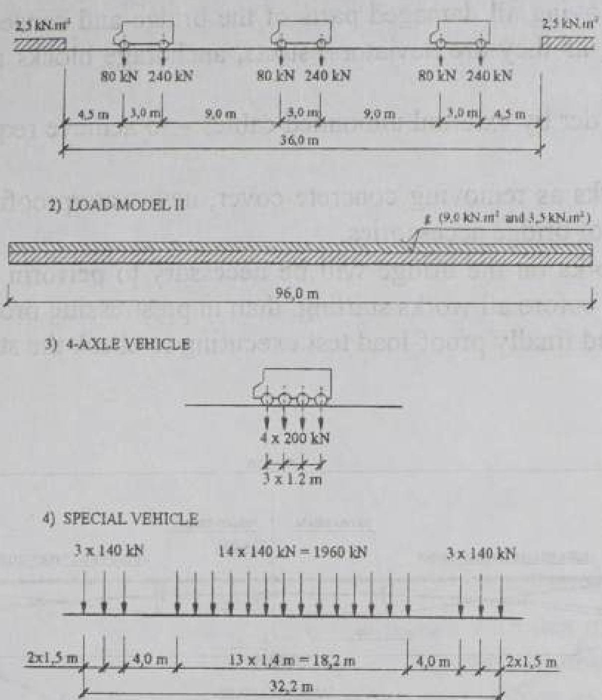

Figure 3. Live Load Schemes According Slovak Standards

Special load case of first group of loads is external prestressing as an artificial load effecting. Unbonded cable effects are substitute by equivalent singular forces P_i according to Fig. 4., which are acting to girder in deviator places. These singular forces depend on prestressing losses which was applied as followed :

- tendon friction inside the ducts – cca 5,8 %
- slip in anchorage device – cca 7,6 %,
- tendons relaxation – cca 5,8 %,
- creep of concrete (t_o is considered around 40 years, that means minimum influence),
- elastic strain of concrete – 1,1 %, that resulted to prestressing losses in internal prestressing too.

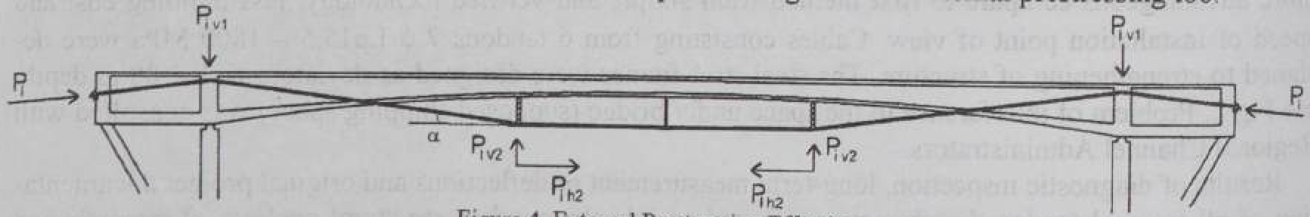

Figure 4. External Prestressing Effecting

As the major feature of unbonded tendons of prestressed systems is less rigidity of concrete element and mutual deformation independence of both elements – concrete and tendon. However, it should be pointed out that the deflection of the system will be rather large, which will result in large elongation in the external prestressing tendons and axial force changing ΔP in the tendons. This force increment ΔP is determined from tendon length changing between anchorage, according to followed conditions,

$$\Delta P \,.\, \Delta L_p + \Delta L_g = 0$$

where ΔL_g is the elongation due to external load including prestressing, ΔL_p is the relative elongation of the tendons against concrete element deformation.

$$\Delta P = \frac{\Delta L_g}{\Delta L_p} = \frac{\int_0^L \frac{M(x).e(x)}{E_c.I_c} dx + \int_0^L \frac{N(x)}{E_c.A_c} dx}{\int_0^L \frac{P.e(x)^2}{E_c.I_c} dx + \int_0^L \frac{P}{E_c.A_c} dx + \int_0^L \frac{P}{E_p.I_p} dx}$$

That relation between prestressing force P and deformation w of concrete structure will be converted to non-linear relation, in order to elasto-plastic behaviour of concrete section and second order theory effect (large deformations) should be considered too. That effect can be expressive in slight structures. This can be solved by iteration mechanism, where the axial forces N(x) and bending moments M(x) have to be adjusted regarding structural deformation w. The significant influence of that effect can be seen in the system that is near by ultimate limit state, where the ductility of the concrete section should be considered. In order of above mentioned sense and the large starting imperfection, the deflection w of the system was analysed using Arc-Length iteration method with constant load increment.

More of prestressed cross sections were analysed. All structural system is consisted from internal and external cables and due to statically indetermined system the secondary internal moments (M) are becoming. Reliability of the system is estimated on allowable stresses level, according our standard Slovak standard [2] and safety factor $s_u = 2,0$ in ultimate limit state was checked too. Ultimate compression stress in edge fibre in concrete is determined with 13,5 or 15,5 MPa values, depends on load combination. Ultimate tension stress in edge fibre is determined with 0 or 0,90 MPa value when the full prestressing is applied. The load carrying capacity computing is based on normal stresses σ evaluation and followed relations depend to load combination were used,

$$V_i = \frac{\sigma_{\lim} - \sigma_{dead} + \sigma_{exter}}{\delta.\sigma_{live}} W_i$$

$$V_i = \frac{\sigma_{\lim} - \sigma_{dead} \pm \sigma_{Temp} + \sigma_{exter}}{\delta.\sigma_{live}} W_i$$

where i is normal (n), exclusive (r), exceptional (e) LCC, W is the vehicle weight and δ is a dynamic factor with value 1,13 for normal and exclusive LCC and 1,05 for exceptional LCC.

5. CONCLUSION

The following results and experiences of the bridge rehabilitation can be declared :

1. Accurate diagnostic inspection, the analysis of the failure reasons and load carrying capacity calculation compose general background for determining the real technical condition of the bridge. In this case a complex approach was applied for investigation of the bridge condition and followed bridge rehabilitation.
2. Method of strengthening and some primary material property for repair work are described in this paper. Using external unbonded prestressing seems to be a simple and effective method of structure strengthening. In this way older prestressed bridge structures can take over live load corresponding to the modern traffic requirements. External prestressing imagines fast way to rehabilitation such types of box girder bridges with relatively lower cost.
3. For structural analysis was used linear finite element method with non-linear deformation alternative. Using external prestressing with 6 tendons 7 ϕ Lp15,5 was achieved (by Slovak Highway Administrator) required values of load carrying capacity to the level $V_n = 31$ tonnes (Normal LCC), $V_r = 96$ tonnes (Exclusive LCC) and $V_e = 143$ tonnes (Exceptional LCC). Sections over the support, in mid-span and around L/4 span are exposed as a critical sections from the load carrying capacity point of view. The course of stresses in upper and bottom fibres for all section from 0 m to mid-span illustrates the Fig. 6. As the decisive load combination was analysed complex load combination - with changing temperature effect (getting warm or cool) with load combination factor 0,7.

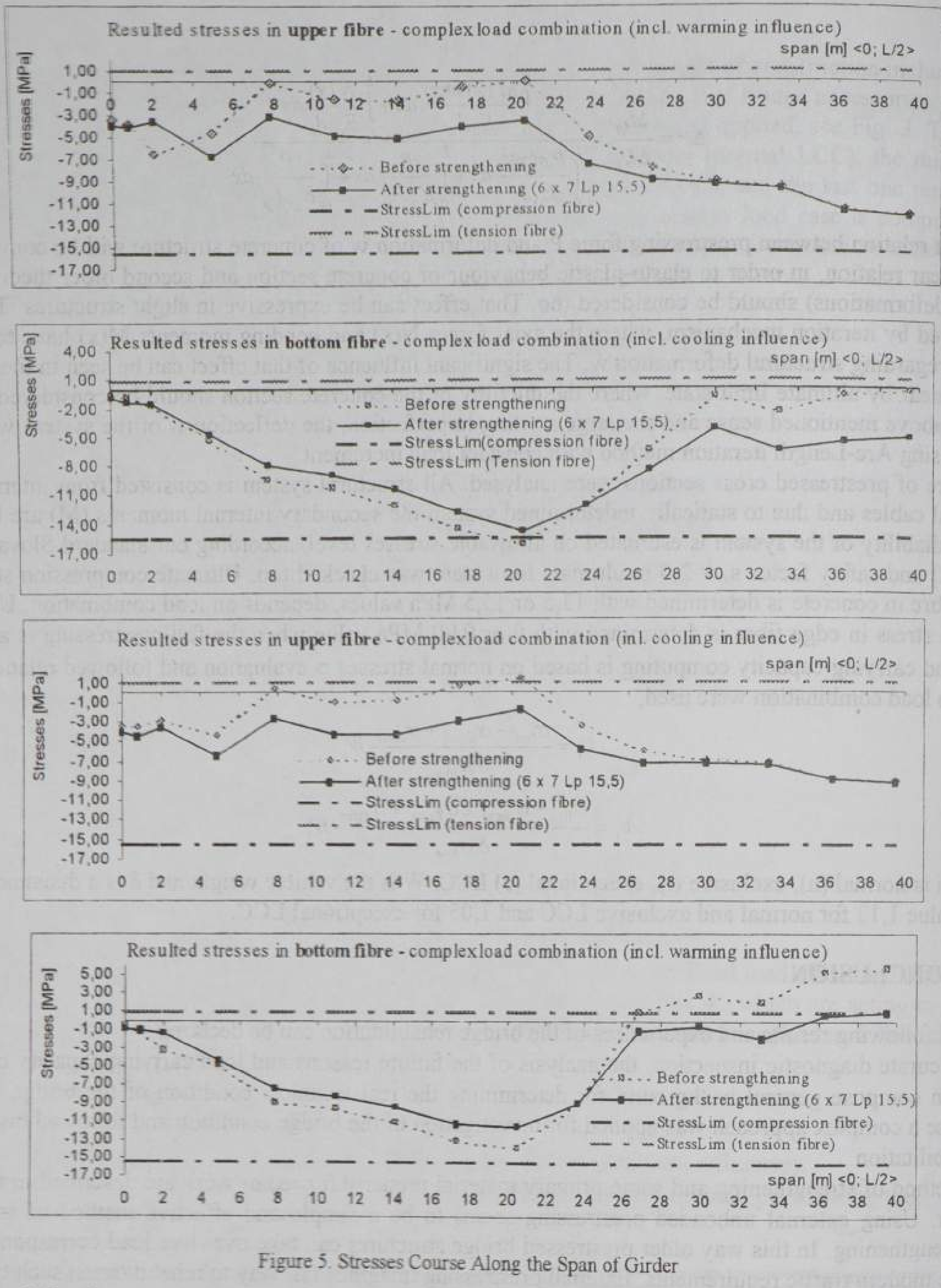

Figure 5. Stresses Course Along the Span of Girder

4. The deflection measurement and its comparing to computed values are recommended within each characteristic step of rehabilitation works : unloading structure with long-term load effects, in prestressing process and static and dynamic proof-load test finally. The efficiency of the used load and live load should achieve 1,0 according to our standard.

Acknowledgements

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УПРУГАЯ ТРЕХСЛОЙНАЯ КОЛЬЦЕВАЯ ПЛАСТИНА

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Объект исследований – несимметричная по толщине упругая кольцевая трехслойная пластина, наружные несущие слои которой выполнены из металла, несжимаемый по толщине внутренний слой (заполнитель) – полимер. Для тонких внешних несущих слоев толщиной $h_1 \neq h_2$ принимаются гипотезы Кирхгофа, для толстого жесткого заполнителя ($h_3 = 2c$), воспринимающего нагрузку в тангенциальном направлении, справедлива гипотеза о прямолинейности и несжимаемости деформированной нормали. Деформации малые. Проекции внешней осесимметричной нагрузки на вертикальную и радиальную оси координат – $q = q(r)$ и $p = p(r)$ соответственно. На внешнем и внутреннем контурах пластины предполагается наличие жесткой диафрагмы, препятствующей относительному сдвигу слоев. В силу симметрии нагрузки прогиб пластины w, относительный сдвиг в заполнителе ψ и радиальное перемещение координатной поверхности u не зависят от координаты φ, т. е. $w = w(r)$, $\psi = \psi(r)$, $u = u(r)$. Эти функции считаются искомыми.

Точное решение задачи линейной теории упругости получено на основе вариационного принципа Лагранжа и выписано в функциях Бесселя:

$$\psi = C_2 I_1(\beta r) + C_3 K_1(\beta r) - K_1(\beta r)\int I_1(\beta r) f(r) r dr + I_1(\beta r)\int K_1(\beta r) f(r) r dr\,;$$

$$w = \frac{b_2}{b_3}\int \psi dr - \frac{a_3}{b_3 a_1}\int L_2^{-1}(p) dr + \frac{1}{b_3}\int L_3^{-1}(q) dr - \frac{C_1 r^2}{4b_3}(\ln r - 1) + \frac{C_5 r^2}{4} + C_6 \ln r + C_4\,;$$

$$u = \frac{a_3}{a_1} w_{,r} - \frac{a_2}{a_1}\psi - \frac{1}{a_1} L_2^{-1}(p) + \frac{C_7 r}{2} + \frac{C_8}{r}\,.$$

Здесь β, a_i, b_i – коэффициенты, зависящие от геометрических и упругих параметров материалов слоев; L_2^{-1}, L_3^{-1} – интегральные операторы; запятая в нижнем индексе обозначает операцию дифференцирования по следующей за ней координате.

Константы интегрирования C_1, ..., C_8 следуют из граничных условий на внешнем и внутреннем контурах пластины. Например, в случае жесткого закрепления обоих контуров они являются решением системы восьми линейных уравнений $u = \psi = w = w_{,r} = 0$ при $r = r_0$ и $r = 1$, при шарнирном опирании они следуют из системы $u = \psi = w = M_r = 0$ при $r = r_0$ и $r = 1$.

С помощью пакета Maple получены константы интегрирования для семи типов закрепления контуров пластины. Численная реализация решения проведена для пластины, несущие слои которой выполнены из дюралюминия, заполнитель – фторопласт. Для семи типов закрепления контуров пластины численно исследовано влияние радиуса внутреннего контура, толщины слоев и характера нагрузки на перемещения (всего около 100 зависимостей). Работа выполнена при финансовой поддержке Министерства образования Республики Беларусь (Поверхность – 52).